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AN INTRODUCTORY MANUAL
FOR YOUNG ENGINEERS AND STUDENTS

BY

ELLIS H. CRAPPER, A.I.E.E.

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SHEFFIELD TECHNICAL SCHOOL

WHITTAKER & CO.
2 WHITE HART STREET, PATERNOSTER SQUARE, LONDON
AND 66 FIFTH AVENUE, NEW YORK
1897

THE NEW YORK
PUBLIC LIBRARY

ASTOR, LENOX AND
TILDEN FOUNDATIONS.
1897.

PRINTED BY
SPOTTISWOODE AND CO., NEW-STREET SQUARE
LONDON

PREFACE

THIS book has been developed from the notes and exercises which the author has prepared for his students in Electrical Engineering at the Sheffield Technical School, and whilst there is not much room for originality in the subject matter of the book, it is hoped that the arrangement and exercises may possess some educational value. Primarily, its scope is educational; the aim of the writer being that of teaching the fundamental principles of Magnetism and Electricity in the laboratory, and of making careful and accurate observations. It is also hoped that it may form a suitable course of instruction for advanced students of organised Science schools, and for first year students of the numerous Technical schools now undertaking such instruction.

Whilst doing this, an endeavour has also been made to give electrical engineering students a familiarity with the principles of measuring instruments; and by including a large amount of quantitative work, to give a training in electrical measurements and in recording experimental results in an intelligent manner, so as to fit them for the testing room of electric light and cable stations. The book is, in fact, an introductory course in

Electrical Testing, and is introductory to a second volume—which is in preparation—dealing with Practical Electrical Engineering, such as the measurement of insulation resistance, ballistic galvanometer work, testing of dynamos and motors, the calibration of measuring instruments, photometry, and alternating current measurements.

The figures consist of sketches of details of apparatus, diagrams of connections, and the arrangement of apparatus. They have been prepared specially to show students the method of representing the arrangement of the apparatus and connections in their note books.

In conclusion, the author desires to acknowledge his indebtedness to the following authors of valuable laboratory manuals: Stewart and Gee, Glazebrook and Shaw, Nichols and Ayrton; and to thank his friend E. J. Bedford, Esq., Science Demonstrator to the Sheffield School Board, for carefully revising the proof sheets, and for making many valuable suggestions.

ELLIS H. CRAPPER.

Sheffield Technical School: *October* 1896.

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CHAPTER I

MAGNETIC FIELDS AND THEIR MEASUREMENTS

Magnetic Fields. *Notes and Definitions.*—Magnetism is the influence in virtue of which certain bodies, called magnets, possess the following distinctive properties:

(1) A tendency to set themselves in a definite direction, parallel to a certain direction in space, called the magnetic meridian.

(2) The power to attract iron filings, pieces of iron and steel, and to deflect magnets that are free to move from their positions of rest.

(3) The power to endue magnetic substances in their vicinity with magnetism, so long as the substances remain in their neighbourhood. Steel retains this magnetism after removal.

Each of these properties implies the existence of force, which in the first case is external to the magnet and is due to the earth's magnetism, whilst in the other cases it springs from the magnet. Consequently, at every point in the neighbourhood of a magnet there is magnetic force, forming a field of force.

Def.—A magnetic field is the region or space within which magnetic force manifests itself.

All magnets and the earth have magnetic fields, and everywhere in such regions the magnetic force has a definite direction and magnitude. In practice it is convenient to make use of a useful conception, by means of which the direction in which the magnetic force acts is indicated by means of imaginary lines, called lines of force.

Def.—A line of magnetic force is an imaginary line in a magnetic field, which at every point is in the direction of the resultant magnetic force at that point.

Magnetic force due to magnets appears to spring from two centres of force or points of maximum intensity, situated nearly at the ends of the axis of the magnet. Such points are called the *poles* of the magnet. The quantity of magnetism acting as if concentrated at a pole is termed the *strength of the pole.* The lines of force of a magnet are partly external and partly internal. The external lines, or briefly the lines of force, emerge from the N or + pole, and enter the magnet again at the S or − pole. The internal lines, which lie within a magnet, are known as *lines of magnetisation.* The *axis* of a magnet is the straight line joining the poles of a magnet.

Def.—A centimetre-gramme-second (*C.G.S.*) *unit magnetic pole is that* N *magnetic pole which exerts a force of one dyne upon an equal magnetic pole one centimetre distant in air.*

The fundamental law of magnetism states that *like magnetic poles repel and unlike magnetic poles attract*, and Coulomb discovered by means of his torsion balance that the magnetic force exerted between two poles is directly proportional to the product of the pole strengths, and inversely proportional to the square of the distance between them. Stated algebraically this is

$$f\text{ (dynes)} = \frac{m \times m_1}{d^2} \text{ (in air)} . \quad . \quad . \quad . \quad (1)$$

where m and m_1 are the pole strengths, and d the distance between the poles in centimetres.

The properties of a magnetic field are completely known when the *intensity of the field* and the *direction of the lines of force* are specified. The strength or intensity of the field is usually denoted by the letter H, and H is measured at any point of a field by the mechanical force in dynes which a unit magnetic pole would experience if placed at that point. A field of unit intensity is such that it exerts a force of one dyne on a unit magnetic pole placed in it. The force in dynes exerted on a magnetic pole of m units strength when placed in a magnetic field where the strength is H units, is equal to the strength of the field, H, at that point in C.G.S. units, multiplied by the strength of the pole, since the force exerted will be m times the force exerted on a unit pole—that is, $f = \mathrm{H} \times m$ . . . . (2)

and H (strength of field at a point) $= \dfrac{\text{force in dynes}}{\text{strength of pole}}$ . . (3)

From this last statement it is clear that if the pole be unity, then the same number denotes the strength of the field at a certain point and also the force exerted at that point. This gives us a means of determining the strength of a field due to a magnet at any point in its field; since, if we assume a N pole of unit strength to be placed at that point, and the pole strength of the magnet to be m, then by equation (1)

$$f = \frac{m \times 1}{d^2},$$

but $f = \mathrm{H} \quad \therefore \ \mathrm{H} = m/d^2$ . . . . (4)

This is only correct when the magnet is so long that the other pole has no effect at the point under consideration. Under ordinary circumstances, when both poles of the magnet influence the strength of the field at the point, then, if l be the length of the magnet in centimetres,

$f = \dfrac{m}{d^2} - \dfrac{m}{(d+l)^2}$ for points along the axis of the magnet produced . . . . (5)

For all other points the directions of the forces due to the two poles make an angle with one another, and to find the resultant force at the point the rules for determining the resultant of two forces in mechanics must be employed. Thus, in fig. 1, if N and S are the poles of the magnet of strength m, and the point P be d centimetres from N and d_1 centimetres from S, then if a unit N pole be placed at P, it is repelled by N with a force $= m/d^2$ dynes, which is denoted in magnitude and direction by the length Pn, and attracted by S with a force $= m/d_1^2$ dynes, which is represented in magnitude and direction by the length P *s*. By completing the parallelogram P *n o s*, the resultant force is represented by the length P *o* to the same scale as before, both in direction and magnitude. That is, the length P *o* to the same scale as P *n* and P *s* represents the strength of the field at P. In this way the strength at any other point may be determined.

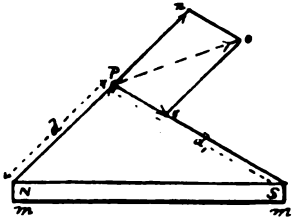

FIG. 1.

The intensity of a magnetic field is often represented by a number of lines of force which are assumed to cut the unit area—1 square centimetre—in a plane at right angles to the direction of the lines. The unit field is thus represented by one line per square centimetre, and a field of H units strength is assumed to have H lines per square centimetre.

Experiment 1 A.—**Maps of Magnetic Fields and Lines of Force.**

Apparatus.—Three bar magnets, 10 centimetres by 1 centimetre by ½ centimetre, marked A, B, C, and unequally magnetised; two similar horse-shoe magnets, several pieces of soft iron, a small flat ring of soft iron about 1½ inches in diameter, fin iron filings in a muslin bag, a sheet of thin glass, several smal compass needles nicely pivoted on needle points.

Sketch the lines of magnetic force mapped out by the filing sifted through the muslin, and let fall from a height of 10 o 12 inches on to the sheet of glass, placed horizontally over th magnets as detailed below. By gently tapping the glass as t filings fall, the magnetic curves will be more distinct. By using gla the positions of the magnets are seen, and they should be show the sketches.

(1) One bar magnet placed horizontally.

(2) Two bar magnets parallel to one another, like poles adj

(3) Two bar magnets parallel to one another, unlike adjacent.

(4) One horse-shoe magnet placed horizontally.

(5) Two horse-shoe magnets placed horizontally, poles forming a square. There are two cases; take both arrangements.

(6) One bar magnet placed vertically, to get field in a plane at right angles to the direction of the axis.

(7) One bar magnet placed parallel to the poles of a horse-shoe magnet.

(8) A piece of unmagnetised soft iron touching one pole of a horse-shoe magnet, and placed so as to make an angle of 45° with the axis.

(9) A piece of unmagnetised soft iron placed parallel to the poles of the magnets in (2) and (5).

(10) A small flat ring of soft iron placed between two poles in (2), (3), and (5).

By placing the small compass needles at different points in the above fields, it will be noticed that they always take up positions as tangents to the lines of force, and the positive direction of the lines of force is that in which the N pole of the needle points. In this way magnetic fields may be mapped out as well as by iron filings.

Exercises.—(1) Write a short account of the characteristic properties of magnetic curves.

(2) Explain *magnetic induction* from the figures due to (8) and (9).

(3) Write a short account of *magnetic screens* or *cages* from (10).

Experiment 1 B.—**Determination of the Direction of Superimposed Fields.**

Apparatus.—Bar magnet and small compass needle with a glass pointer freely suspended within a glass jar, as shown in fig. 2. On the base of the instrument and immediately under the needle a circular scale graduated in degrees is fixed, the diameter of which is slightly smaller than the diameter of the jar.

The following are useful examples of the way the magnet field at a point due to a magnet may *coincide and augment*, *oppose and diminish or neutralise*, the field due to the earth at that point. If a magnetic field exists at a point the suspended needle always indicates its direction. If no field exists the needle will come to rest in any position.

Practical Exercises.—(1) Determine the magnetic meridian by means of the suspended needle, and then place a bar magnet in the meridian about 10 centimetres from the centre of the needle, (*a*) with the N pole pointing north, (*b*) with the S pole pointing north, and occupying the place previously occupied by the N pole. Determine the direction of the resultant field in each case.

(2) With the S pole of the magnet pointing north (and still in the meridian) find the position of the magnet where the earth's influence on the needle is neutralised. To do this move the magnet until the needle comes to rest in different positions when displaced.

(3) Draw a line at right angles to the meridian through the centre of the needle, and place the bar magnet to the west of the needle in a line parallel to the meridian, so that the E and W line bisects the axis of the magnet about 5 centimetres from the centre of the needle, (*a*) with the S pole of magnet pointing north, (*b*) the N pole pointing north. Determine the direction of the resultant field at the point occupied by the needle.

(4) Describe a circle of 10 centimetres radius about the point of intersection of the line at right angles to the meridian (in 3) with the magnetic meridian, and place the magnet A, pointing east and west, with its centre on the circle, and note the deflection of the needle suspended at the centre of the circle. Do this for twelve positions (30° apart) on the circle, in each case keeping the magnet pointing east and west.

Exercise.—Prove, graphically, that the results obtained in (3) are consistent with the statements made with reference to fig. 1.

Experiment 1 C—**Measurement of Magnetic Force and Strength of Field at any Point by Method of Deflection.**

Apparatus.—The three bar magnets A, B, C; the small suspended magnetic needle with scale (fig. 2); large sheet of drawing paper on drawing board, together with meter rule.

(1) Draw two lines across the paper at right angles to one another, and place the board so that one of the lines coincides

with the magnetic meridian. Mark this line N S, and the other E W. Place the suspended needle at O, the intersection of the lines N S and E W, and the bar magnet A to the west of the needle, in the E and W position as shown in fig. 3. This position is known as the ***ena-on*** position. In consequence of the superposition of fields we have now at O, (1) the field due to the earth's magnetism, the direction of which is N and S, and which is of constant intensity, denoted by H ; and (2) a field due to the magnet A, in the direction O E, the intensity of which depends upon the distance of A from O, according to equation (5). Let F denote the strength of the field at O due to A ; and by varying the position of A it will be noticed that the suspended needle takes up different positions, which in all cases are in the direction of the resultant field. Move A until the needle makes an angle of 45° with N O. Then it is clear that since O ***n*** bisects the angle N O E, the two component fields H and F at O are equal. In other words, H = F. In this way we have the means of determining the strength of the field at a point due to a magnet, since the intensity of the earth's field is constant and a known quantity. For our purpose H may be taken as ·18, and by noting

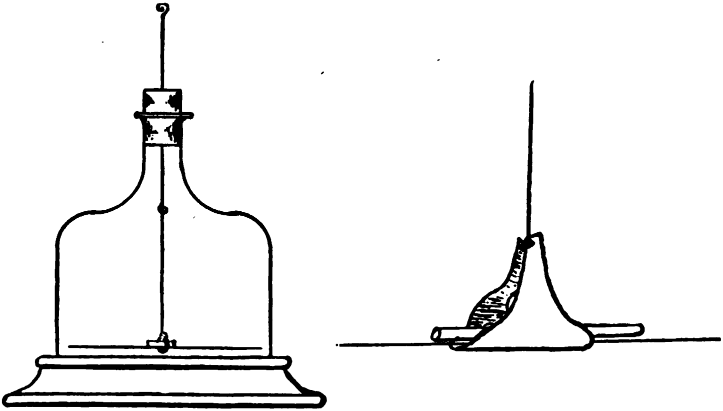

FIG. 2.

the distance of A from O we can calculate the pole strengt from equation (5). Remove A and place another bar magnet, the *end-on* position, to the east of the needle, the N pole facing the needle. Find the position of B for a deflection o As before, $F_1 = H$, F_1 being to the strength of the field at O du Place A as before, B being still to the east, and note the r The fields due to A and B are now in the same straight line,

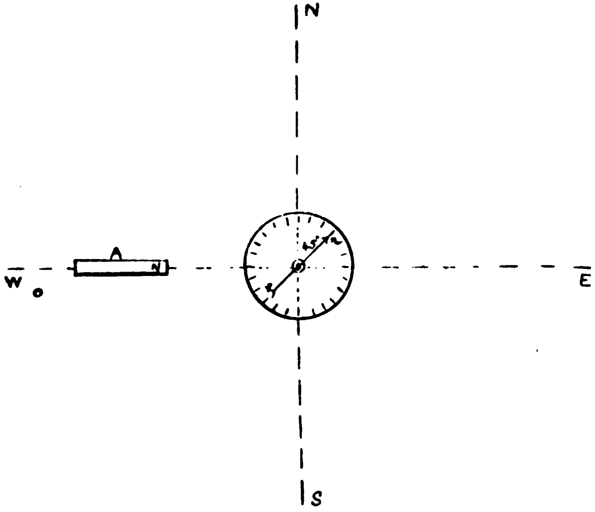

FIG. 3.

and, being *equal* and in *opposite directions*, their resultant at zero, and consequently the suspended needle is only under action of the earth's field. By doing the same with A and C, a and C, we can determine relatively the pole strengths of A, B, a Again, take the two bar magnets A and B, and place them in positions already determined, B being inverted so that the S takes the place of the N pole, and as their fields at O are *equal co-directional*, their resultant field at O is $F + F_1$, or $2F$; and s

F = H, the magnitude of their resultant field at O equals 2 H, or twice the earth's field, and it will be found that the suspended needle now makes an angle of 63° 26′ with N O.

Practical Exercises.—Perform the preceding Experiments as directed, and enter the Results in a Tabulated Form as follows:

Experiment	Magnet on W side distance of nearest pole		Magnet on E side distance of nearest pole		Mean distance in cms.	Value of *m* calculated from $F = m/d^2 - m/(d+l)^2$	Angle of Deflection
	N adjacent	S adjacent	N adjacent	S adjacent			
	cms.	cms.	cms.	cms.	cms.		degs.
A alone	13·25	13·25	13·25	13·25	13·25	43·5	45
B alone	11·25	11·0	11·0	11·0	11·0	28·25	45

Tangent Law.—These results are very important, and from them we may deduce a rule for the comparison of magnetic fields quantitatively which is known as the *tangent law.* By means of fig. 4 and the results obtained above this law may be explained. The position of the suspended needle when only A is present is denoted by O P, and by O P_1 when both A and B are present, as in the last experiment.

First Case.—Complete the parallelogram O *n* P *p*, and let O *n* and O*p* to some scale represent H and F respectively, in magnitude and direction. From the geometry of the figure it is evident that

$\mathrm{O}n = \mathrm{O}p = n\mathrm{P}$ and $\frac{\mathrm{P}n}{\mathrm{O}n}$ = tangent of the angle $\mathrm{PO}n = \tan 45°$.

$$\therefore \frac{\mathrm{F}}{\mathrm{H}} = \tan 45° \text{ and } \mathrm{F} = \mathrm{H} \tan 45° ;$$

but $\tan 45° = 1 \quad \therefore \frac{\mathrm{F}}{\mathrm{H}} = 1$ and $\mathrm{F} = \mathrm{H}$.

Second Case.—Similarly, let Op_1 and $\mathrm{P}_1 p_1$ to a certain scale represent F_1 and H respectively, and as before

$$\frac{\mathrm{O}p_1}{\mathrm{P}_1 p_1} = \text{tangent of angle } \mathrm{OP}_1 p_1 = \tan \mathrm{P}_1 \mathrm{O} n_1$$

and by experiment we have found that the angle $P_1 O n_1 = 63° 26'$

$$\therefore \frac{F_1}{H} = \tan 63° 26' \text{ and } F_1 = H \tan 63° 26'$$

From a table of natural tangents we find that $\tan 63° 26' = 2$, $\therefore \frac{F}{H} = 2$ or $F = 2H$, a result which agrees perfectly with the reasoning above. Hence the following law:

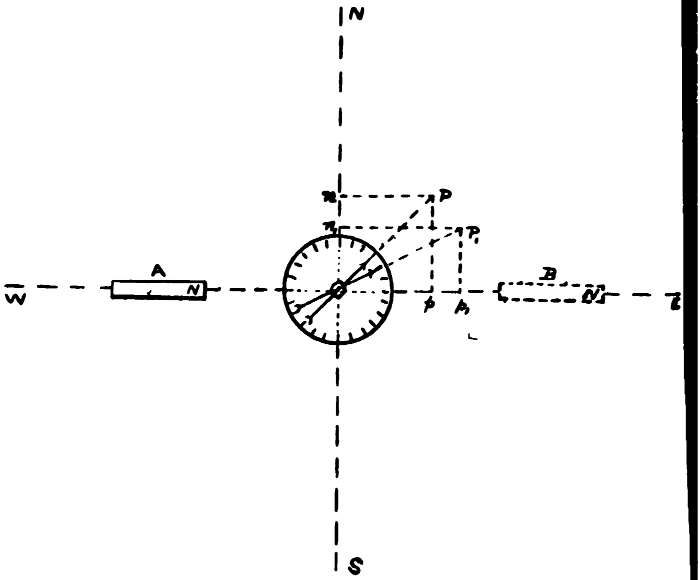

FIG. 4.

If two magnetic fields, the directions of which are at right angles to each other, are superimposed at a point, and a compass needle be placed at this point, it takes up a position which indicates the resultant field at that point, which is such that the axis of the needle makes an angle θ with the direction of one of the fields, the tangent of which is equal to the ratio of the other field to this field.

Thus, if the two fields are H and F, and the needle makes an angle θ with H, then

$$\frac{F}{H} = \tan\theta \text{ and } F = H\tan\theta \quad . \quad . \quad . \qquad (6)$$

In practice, the intensity of a field due to a magnet at any point is compared with the earth's field at that point, H being taken as ·18, unless another value is given.

Experiment I D.—**The Proof of the Tangent Law.**

Apparatus.—As in I C.

List of Experiments.—(1) Prove the tangent law by combining A and C and B and C, as in the last experiment above.

(2) Prove the tangent law by adjusting the three magnets A, B, C, so as to give successive deflections of 30°, 45°, 60° in each case.

(3) Determine the pole strengths of A, B, C by getting deflections of 60° and using equation (5).

In all cases invert the magnets and take readings on both sides —E and W—of the needles, so as to get the mean of the quantities determined.

(1) *Exercises.*—Prove that the value of F given in equation (5)

$$= \frac{2mlx}{\left(x^2 - \frac{l^2}{4}\right)^2},$$

if x is the distance between the centre of the magnet and O.

(2) Calculate the strength of the field due only to a magnet of pole strength 10 units and length 10 centimetres at a point 5 centimetres distant from the centre of the magnet on the normal line.

Answer : 0·283 unit.

Experiment I E.—**To Prove the Law of Inverse Squares.**

Apparatus.—A suspended needle with scale as in I C; a long thin knitting-needle about 30 centimetres long, strongly magnetised, and supported as shown in fig 5; a sheet of paper on drawing-board with N and S and E and W lines.

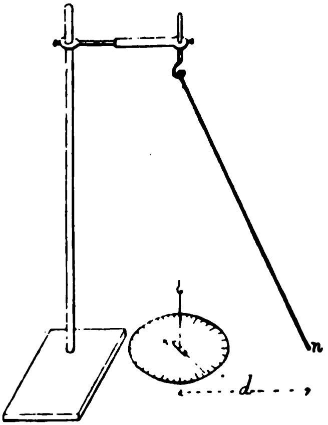

FIG. 5.

If the long magnetised needle be placed with its upper or S pole directly over the centre of the suspended needle, that pole will exert no effort to deflect the needle. And it is obvious that if the lower or N pole of the long needle be placed on the E and W line at the same level as the suspended needle, we shall get a definite magnetic field at the centre of the suspended needle, the direction of which will be E and W. The intensity of this component, denoted by F, depends upon the distance and the strength of the single pole N. The ratio of the strengths of the two fields—that due to the pole N, and that due to the earth—or $\frac{F}{H}$ is proportional to the tangent of the angle of deflection, as explained in experiment I C. By varying the distance and noting the deflection we can determine within certain limits how F varies with the distance.

And here it may be well to point out that the results obtained by experiment vary, in some cases very considerably, and it is a useful exercise to assign the probable cause of such variations, and to determine the methods to adopt in order to reduce or eliminate them.

These variations are due to errors which arise from a variety of causes, some of which will now be enumerated. (1) *Constant errors*, due to inaccuracies in the construction of the instruments; for instance, much practice is needed to perfectly suspend a magnetic needle and a pointer, to graduate a scale in degrees, &c. (2) *Accidental errors* in manipulation. (3) *Errors of observation*, as in reading the deflection of a magnetic needle, especially if the scale be only divided into spaces containing ten degrees. (4) *Errors of method;* for instance, it will be noticed that in the tabulated results given below the value of *m* is more accurate when the deflection is betweeen 30° and 60° than when the angle is smaller or larger than these limits. By referring to the table of natural tangents it is obvious that the percentage of error due to a wrong reading is least about 45°. Thus, supposing an error of observation of 1° is made when the deflection is 20°, 45°, and 70° respectively, the percentage of error in each case is as follows :

Tan 20° = ·3640	tan 45° = 1·0000	tan 70° = 2·7475
Tan 19° = ·3443	tan 44° = ·9657	tan 69° = 2·6051
Difference = ·0197	difference = ·0343	difference = ·1424
% of error = 5·5	% of error = 3·4	% of error = 5·3

These are not extreme cases, the error increasing as smaller and larger angles are taken, and it follows that a selection should be made, and only the results between certain limits accepted as correct ones.

The following is the method of tabulating the results obtained in this exercise, showing in columns 8 and 9 that the results are correct to within about 1 per cent.

Expt.	Distance in cms.	Deflection		Mean Deflection θ	Tan θ	Value of F, taking H = ·18	Ratios of Fields	Inverse Ratios of Distances Squared	Calculated Value of *m*
		W side	E side						
1	15	20° 30′	22°	21° 15′	·3889	·07			15·68
2	14	22° 30′	25°	23° 45′	·4400	·0792	·88	·87	15·45
3	13	26° 30′	27°	26° 45′	·5040	·09072	·87	·86	15·26
4	12	30°	30°	30°	·5774	·103932	·88	·85	14·97
5	11	34° 30′	34° 30′	34° 30′	·6873	·123714	·84	·84	14·97
6	10	39° 30′	39° 30′	39° 30′	·8243	·148374	·83	·82	14·84
7	9	45°	45°	45°	1·0000	·18	·82	·82	14·51
8	8	52°	52°	52°	1·2799	·230382	·78	·79	14·68
9	7	60°	57° 30′	58° 45′	1·6479	·296622	·77	·76	14·46
10	6	67° 30′	63°	65° 15′	2·1943	·394974	·75	·74	14·16

Mean value of *m* = 14·91

Practical Exercises.—(1) Determine the deflection when th long needle is placed on the E and W line, at distances varyin from about 15 to 5 centimetres[1] from the centre of the suspende needle.

(2) Determine the position on both sides of the meridian fo which the field at the centre of the suspended needle is equal t that of the earth. As before, the deflection will be 45°.

Exercises.—(1) Form a series of ratios of the strengths of field taken two at a time, and compare them with the inverse ratios o the corresponding distances squared.

(2) Calculate the value of m from the equation $F = m/d^2$ in each case, and enter the result in the last column, as shown above.

(3) Prove that $\tan\theta = \frac{m}{d^2} \Big/ H$ from first principles in mechanics, and from the geometry of the arrangement.

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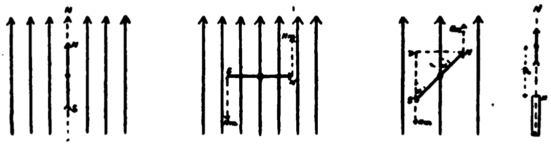
[1] In this and other tests the distances taken will depend upon the strength of the magnets used.

CHAPTER II

ACTION OF A MAGNETIC FIELD ON A MAGNET OR NEEDLE

Magnetic Moment. *Notes and Definitions.*—A magnetic needle suspended at its centre by a torsionless fibre, and free to rotate in a horizontal plane, sets itself so that its axis coincides with the direction of the lines of force of the field in which it is placed. The force keeping it in its position of equilibrium is equal to the product of the strength of the field (H) and the pole strength (m) of the needle—that is, $F = H\,m$ dynes.

If this needle be placed at different points in a field, and it is found that the magnitude of the force exerted upon the needle is



a *b* *c* *d*

Fig. 6.

the same at all points, the field is said to be a ***uniform magnetic field***. The earth's field for any place is uniform, and the value of H due to the earth's magnetism is absolutely constant for fairly large areas, and at all points there will be H lines of force per square centimetre. Such a field is represented graphically by parallel straight lines at equal distances apart, as in fig. 6, *a*.

When the needle is placed with its axis at right angles to the direction of the field, as in fig. 6, *b*, a force of H m dynes is experienced at both ends of the needle, tending to restore it to its position of equilibrium in the meridian; consequently a force of $H m$ dynes must be applied at each end, in the opposite direction to that of the field, if we wish to keep it where it is. The effect of these forces is a tendency to produce rotation, which tendency is proportional to the intensity of the forces and the length of the needle.

Def.—The tendency of a force to produce rotation about a point is termed the "moment of the force," and numerically the moment of a force is equal to the product of the force into the perpendicular distance from the point. That is,

$$\text{Moment of a force} = F \times \text{perpendicular distance,}$$

$$= H m \frac{l}{2} \text{ in the example of fig. 6, } b.$$

It is obvious from inspection of fig. 6, *b*, that the moment of the force acting on the N pole is equal to the moment of that acting on the S pole; and since they both tend to rotate the needle in the same direction, the total tendency to produce rotation is twice $H m \times \frac{l}{2}$, or $H m \times l$, l being the distance between the poles of the magnet. In mechanics the combination of two equal, parallel, but opposite forces constitutes what is termed a *couple*, and the perpendicular distance between the lines of action of the forces is termed the *arm of the couple.* In the case under consideration the moment of the couple—*i.e.* the tendency to rotate or *torque*, as it is called, is $H m \times l$, which is the product of two factors—H, the strength of the field, and $m l$, the product of the pole strength and the length of the magnet. If $H = 1$—that is, if the field be of unit strength—the torque is equal to $m \times l$, and for this reason the product of the pole strength of a magnet and its length is termed the *moment of the magnet.*

Def.—The moment of a magnet is the product of its pole strength and the distance between the poles, and is the measure of the tendency of the magnet to rotate, when placed at right angles to the meridian in a field of unit strength.

The moment of a magnet is denoted by the letter M,

$$\therefore \text{M} = m \times l \quad . \quad . \quad . \quad . \quad . \quad (7)$$

and the moment of the couple = $\text{H} \times \text{M}$.

The *unit* of the moment of a force or couple is the dyne-centimetre—that is, a force of one dyne (unit force) acting through a perpendicular distance of one centimetre. When the axis of the needle makes an angle a, other than 90°, with the direction of the field, as in fig. 6, *c*, the perpendicular distance or arm of the couple is P N, and

$$\text{the moment of the couple} = \text{H}\, m \times \text{P N}\ ;$$

and since N P S is a right-angled triangle, and the angle $\text{N S P} = a$

$$\frac{\text{N P}}{\text{N S}} = \sin a\ ;\ \therefore\ \text{N P} = \text{N S} \times \sin a = l \sin a.$$

In this way the arm of the couple is expressed in terms of the length of the needle, which is a known quantity ; therefore

$$\left.\begin{aligned}\text{the moment of the couple} &= \text{H}\, m \times l \sin a \\ &= \text{H M} \sin a\end{aligned}\right\} \quad . \quad . \quad (8)$$

From this equation it is evident that the maximum couple is experienced when $a = 90°$, and is then = H M, since $\sin 90° = 1$. When $a = 0°$ no couple exists, since $\sin 0° = 0$, as in fig. 6, *d*.

Experiment 2A.—**Comparison of Moments of Magnets.**

Practical Exercises.—(1) Magnetise three knitting-needles 12, 8, and 6 centimetres long respectively, by rubbing them the same number of times across one pole of a bar magnet, and place them in turn on a piece of cork floating in water, at right angles to the meridian. If magnetised equally, it will be found on releasing them that the rapidity with which they return to the meridian is approximately proportional to their lengths.

(2) Magnetise three knitting-needles of equal length by rubbing them across a bar magnet 50, 30, and 20 times respectively, and similarly compare the rapidity with which they return to the meridian.

(3) Break a uniformly magnetised knitting-needle into two pieces, one twice as long as the other, and fasten the two pieces

vibrating needle, situated at this point, as in fig. 6, *d*. And if the various magnets are equal in length, then

$$\left(\frac{1}{d^2}-\frac{1}{(d+l)^2}\right) \text{ in the formula } F = m\left(\frac{1}{d^2}-\frac{1}{(d+l)^2}\right)$$

s the same in each case, from which it follows that F_1, F_2, &c., are respectively proportional to m_1, m_2, &c., the pole strengths of the magnets used. The method of vibrations is thus applicable for comparing the pole strengths of magnets.

To determine the value of the ratio $\frac{F_1}{F_2}$ from the number of oscillations, we proceed as follows :—

Since $M H = K n^2$, $M (H + F_1) = K n_1^2$, and $M (H + F_2) = K n_2^2$,

$$\therefore \frac{M F_1}{M F_2} = \frac{K n_1^2 - M H}{K n_2^2 - M H} = \frac{K n_1^2 - K n^2}{K n_2^2 - K n^2},$$

and $$\frac{F_1}{F_2} = \frac{n_1^2 - n^2}{n_2^2 - n^2}. \qquad (12)$$

and $\frac{m_1}{m_2} = \frac{n_1^2 - n^2}{n_2^2 - n^2}$, if the magnets are of the same length and similarly situated.

Practice of the Method.—The principle of the method just explained is very simple, but in practice great care must be taken to get reliable results, and it is necessary that two students should work together, one to count the oscillations, and the other to take the time. The method of procedure is as follows : The suspended needle or magnet is placed in a bell-jar or other glass vessel, with its centre at the place where the test is to be made. The vibrating needle is displaced from its position of rest, preferably by bringing another magnet near for a moment, and when the extent of swing is about 5° on each side of the meridian, and the needle is swinging evenly, the one counting gives the signal to the one taking the time by calling out '*now*' when the needle is at the extent of the swing on one side, and '*nought*' when the needle passes the meridian, and the time when '*nought*' is called is accurately noted by the companion. The one counting then calls '*and*' when the other extent of the swing is reached, and '*one*' when it passes the meridian in its return, and '*and*' again when the other extent is reached. The counting is then continued thus: *two and*, *three and*, *four and*, &c., until as large a number as possible has been counted, the larger the number the better. When the counting is finished a signal again is given, and the time noted. It will be noticed that the number counted gives the *transits*, and since two transits make one oscillation, the number of oscillations is half the number of transits. The advantage of calling *and* gives 0·25 of an oscillation, which it is necessary to notice if the counting is only continued for a definite period of time, as, say, one minute, as is frequently done, although a longer period of time gives more accurate results. The method of entering the oscillations and time is as follows:

Time of Oscillation.

	hrs.	min.	sec.
Time of 260th passage . . .	2	32	10
Time of 0th passage	2	30	0
Time of 260 oscillations		2	10

Time of 1 oscillation = $\frac{130}{260} = \frac{1}{2}$ sec.

Or 2 oscillations per second.

Practical Exercises.—(1) Prove that the oscillations of a magnetic needle are isochronous by displacing the needle through 20°, 15°, and 10° respectively, and counting the number of oscillations per minute in each case.

(2) Compare the intensity of field set up by a magnet at the point occupied by the needle when the magnet is 4, 6, and 8 centimetres distant from the centre of the needle.

(3) Compare the pole strengths of the bar magnets A, B, and C by suspending them in turn by means of torsionless fibres. Note $\frac{M_1}{M_2} = \frac{n_1^2}{n_2^2}$, assuming that the moment of inertia is the same in each case.

(4) Prove by the method of vibrations that when the N pole of the long knitting-needle of Experiment 2 A is placed at the same distance from the centre of the suspended needle as was determined

in Exercise 2 of Experiment 2 A, but in the meridian and to the south, the resultant field is twice that due to the earth.

Note $\frac{H + F_1}{H} = \frac{n_1^2}{n^2}$, and n_1^2 = twice n^2 (approximately).

(5) Determine the distribution of magnetism along a bar magnet by placing the vibrating needle at different points near the magnet, held vertically, and enter results as shown in fig. 7.

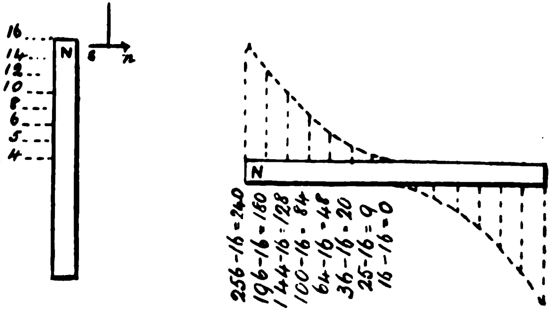


FIG. 7.

Exercises.—(1) Calculate the pole strengths of magnets A, B, and C from the results obtained in (3) above.

(2) A needle makes 41 oscillations per minute when the N pole of a bar magnet is placed a certain distance away, and 24 when the positions of the poles of the bar magnet are reversed. Find the time of an oscillation under the action of the earth's force alone.

Answer: $\frac{1}{33{\cdot}5}$ min.

CHAPTER III

ACTION OF A MAGNET UPON ANOTHER MAGNET

Theory of Method.—It will probably have been noticed that in the exercises on magnetic fields, already given, that Coulomb's law of the inverse square of the distance is only true when the field is due to one pole, and that when a field is due to the two poles of a magnet the law of inverse squares does not hold for all distances. We shall therefore now show how to determine the law which holds when the action is between magnet and magnet situated in a field of uniform strength, H. By arranging that one of the magnets shall be a freely suspended magnetic needle, we shall be able to find the value of the moment of the other magnet in terms of the strength of the field in which they are placed, the angle of deflection, and the distance between the centres of the magnets. There are two cases to consider, depending on the position of the magnet relative to that of the needle.

First Case: 'End-on' Position.—This corresponds to experiment I C, a powerful magnet being placed horizontally with its axis on the E and W line, normal to the meridian, in which is suspended, at a certain distance from the centre of the magnet, a *very small* needle, as shown in fig. 8.

Let l and m be the length and pole strength of magnet N S.
l_1 and m_1 „ „ „ needle n s.
d the distance between the centres of the needle and magnet.

The moments of the magnet and needle are respectively:

$$M = m \times l$$
$$M_1 = m_1 \times l_1.$$

From experiments already performed we know that the suspended needle *n s* is under the influence of two forces:

(1) The horizontal component of the earth's magnetism in a north and south direction, and

(2) That due to the two poles of the magnet N S in a direction normal to the meridian;

and as a result of the action of these forces the needle takes up a position coinciding with the direction of the resultant field, making an angle a with the meridian. In this position of equilibrium the attractive and repulsive forces exerted on the poles of the needle by the magnet may be considered equal, since the needle is so small that the distances S *n* and S *s* are approximately equal to S O, and in like manner N O may be taken as being equal to the distances between N and the poles *n* and *s* of the needle. In the figure the needle is shown enlarged, so that students may see that the directions of the individual forces, *n f* and *s f*, due to the magnet may, without serious error, be taken as being parallel to S O, and thus practically form a couple, the arm of which is *p s*; and calling the force acting on the poles of the needle F, then the moment of the couple is F × *p s*.

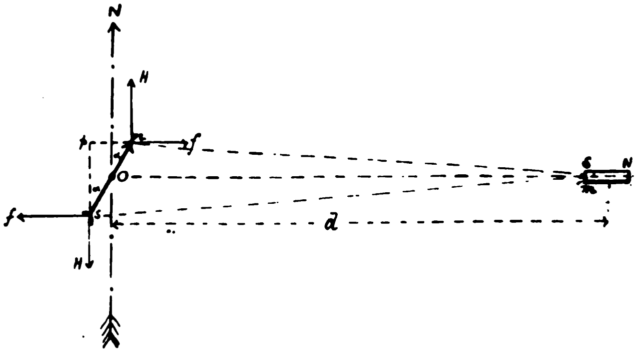


FIG.

But $p\ s = l_1 \times \cos a$.

∴ the moment of the couple due to the magnet $= \mathrm{F}\, l_1 \cos a$, and from equation (8) we know that the moment of the couple due to the earth's magnetism $= \mathrm{H}\, m_1\, l_1 \sin a$, and since the needle is in a position of equilibrium, these two moments are equal:

$$\therefore \mathrm{F}\, l_1 \cos a = \mathrm{H}\, m_1\, l_1 \sin a \quad . \quad . \quad . \quad (13)$$

To determine F, we apply Coulomb's law of inverse squares, and get

$$\mathrm{F} \text{ acting on } n = m\, m_1 \left\{ \frac{1}{\left(d - \frac{l}{2}\right)^2} - \frac{1}{\left(d + \frac{l}{2}\right)^2} \right\} = \frac{2\, m\, m_1\, d\, l}{\left\{ \left(d - \frac{l}{2}\right)\left(d + \frac{l}{2}\right) \right\}^2}$$

$$\mathrm{F} \text{ acting on } s = m\, m_1 \left\{ \frac{1}{\left(d - \frac{l}{2}\right)^2} - \frac{1}{\left(d + \frac{l}{2}\right)^2} \right\} = \frac{2\, m\, m_1\, d\, l}{\left\{ \left(d - \frac{l}{2}\right)\left(d + \frac{l}{2}\right) \right\}^2}$$

since $\mathrm{S\,O} = d - \frac{l}{2}$, and $\mathrm{N\,O} = d + \frac{l}{2}$.

If l is small compared with d, we may regard

$$\left(d - \frac{l}{2}\right)\left(d + \frac{l}{2}\right) = d^2,$$

and the denominator in the above fractions becomes d^4, without introducing any serious error, and since $m\, l = \mathrm{M}$, each of the above forces becomes

$$\mathrm{F} = \frac{2\,\mathrm{M}\, m_1}{d^3} \quad . \quad . \quad . \quad . \quad . \quad . \quad (14)$$

Substituting this value in (13), we get

$$\frac{2\,\mathrm{M}\, m_1\, l_1 \cos a}{d^3} = \mathrm{H}\, m_1\, l_1 \sin a,$$

from which

$$\frac{\mathrm{M}}{\mathrm{H}} = \frac{d^3 \sin a}{2 \cos a} = \frac{d^3}{2} \tan a \,. \quad . \quad . \quad . \quad . \quad (15)$$

From this equation it is evident that the product of the cube of the distance into the tangent of the angle of deflection is a constant quantity, and that as d^3 increases $\tan a$ decreases, and *vice versa*, from which it follows that the force varies inversely as the cube of the distance, as shown in equation (14). This is true when the distance between the centres is not too small, *i.e.* not less than four or five times the length of the magnet.

Second Case. Broadside Position.—In this case the magnet N S is still pointing E and W, but placed so that the magnetic meridian, in which the suspended needle is placed, is normal to and bisects the axis of N S. As before, the needle *n s* is shown enlarged for the sake of showing graphically how the result given below is obtained. The letters of reference and the method of determining the value of M of the magnet are exactly the same as in the case just given, so that by following fig. 9 the student should be able to prove that in the broadside position

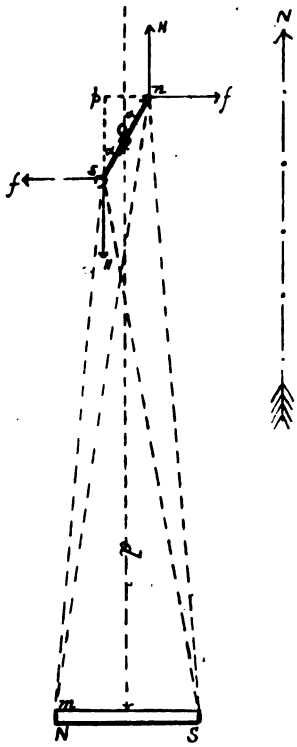


FIG. 9.

$$\frac{M}{H} = d^3 \tan a. \qquad (16)$$

The '*end-on*' and '*broadside*' positions are also known as the A and B tangent positions of Gauss.

Experiment 3 A.—**To Prove the Formulæ of the A and B Tangent Positions of Gauss.**

Apparatus.—Several bar magnets; a suspended needle as in previous experiments; a platform for supporting magnet and needle, consisting of two wooden slides, each two metres in length, crossing each other at right angles, each marked with metre scale as shown in fig. 10. The two wooden slides will be required in exercises (2), (3), and (4).

Practical Exercises.—1. Place a bar magnet, on the E and W diameter, at the centre of a circle the diameter of which is at least five times the length of the magnet. Prove that the force at the extremities of the N and S diameter of the circle is half that at the extremities of the E and W diameter by placing the suspended needle on the circumference of the circle at the four cardinal points.

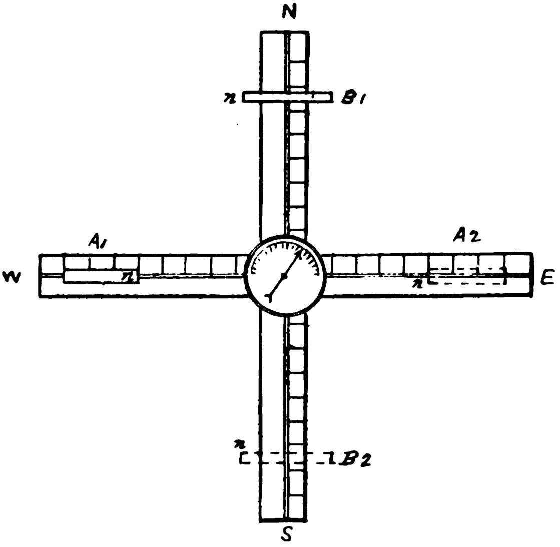


FIG. 10.

Note.—Since d^3 will be constant, tan $a = \frac{1}{2}$ tan a.

2. Place a magnet in the *broadside position* at 25, 35, and 50 centimetres distance, and prove that the tangents of the angles of deflection are inversely as the cubes of the distances.

3. Compare the moments of two magnets by placing them separately in both the A and B positions, (1) by keeping the distance

the same in each case, (2) by keeping the angle of deflection same in each case.

4. Determine the value of $\frac{M}{H}$ with one of the magnets, distances of 30 and 40 centimetres, using the A and B positio and tabulate the results as shown below. In all cases the mag should be reversed and readings taken on both sides of t needle, giving four readings for each position.

Experiment	Position	Distance	Deflection	Mean Deflection	Value of $\frac{M}{H}$ calculated
1	A_1	30 cms.	30·2°	30·2°	7857
	A_2	,,	30·25°		
	A_3	,,	30·15°		
	A_4	,,	30·2°		
2	B_1	,,	16·25°	16·2°	7843·5
	B_2	,,	16·2°		
	B_3	,,	16·2°		
	B_4	,,	16·15°		

Mirror Magnetometer.—In the above experiments the results obtained will probably vary, since the suspended needle magnetometer does not permit of accurate readings, the angles of deflection being small, and consequently difficult to read. To avoid this difficulty, and to obtain more accurate results, the method of utilising the reflection of a ray of light from a very small mirror, upon the back of which the small magnetic needles are fastened, is much used as a means of measuring the angles through which the magnetic needle moves. A very convenient form of magnetometer is one in which the small suspended magnet is attached to a mirror freely suspended, as shown in fig. 11. From the figure it will be seen that the mirror magnetometer consists of a long narrow groove or chamber, terminating at the bottom in a flat circular recess, in which

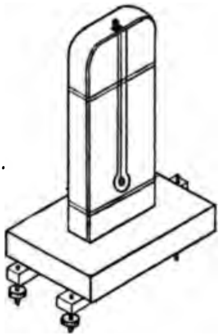


FIG. 11.

is suspended, by means of a torsionless fibre, one or more short magnetic needles, attached to the back of a small concave mirror of known focal length. The fibre hangs freely in the groove, and the mirror is free to rotate through a small angle in the recess. A piece of glass placed in front of the groove, and held in its place by means of elastic bands, protects the mirror from draughts of air. In using the magnetometer a ray of light from a lamp, placed behind a screen on which a scale is fixed, is reflected by the mirror back to the scale. The reflected ray takes the place of the pointer previously used, and, since it is weightless, it is an advantage to arrange for it to be of great length, so that very small deflections may be accurately determined. In fixing up this instrument care must be taken so as to get the mirror to swing freely, and when at rest under the action of the earth's magnetism its plane should coincide with the meridian. The screen with the scale should be perfectly parallel to the plane of the mirror, and at the proper distance from it, to get a distinct image of the spot of light. The image of the spot of light when the mirror is in the meridian will be on the middle division of the scale if everything is set perfectly.

In fig. 12 *a* a plan of the arrangement is given. M is the mirror of the magnetometer, the base of which is provided with three levelling screws, shown as circles, two of which rest in the groove V in a board C, fastened rigidly at right angles to the screen S O S. By this means the magnetometer is kept parallel to the screen, and may be readily moved parallel to itself along the board, so as to get the proper distance between the mirror and scale placed on S O S. L is the lamp placed behind the screen. A and B are blocks of wood of such a height that the bar magnet may be at the same level as the magnets on the mirror. These blocks can be readily moved into different positions, and the positions shown are the A and B tangent positions of Gauss. Fig. 12 *b* shows the angle of deflection a, and the incident and reflected rays O P and P I, P being the centre of the mirror, and O the slit in the screen through which the light passes. I is the position of the image on the scale when the mirror is deflected. P T is the perpendicular to the mirror in its deflected position, and by the laws of reflection we know that the incident and reflected rays make the same angle with the normal P T as the mirror makes with its original position. It will

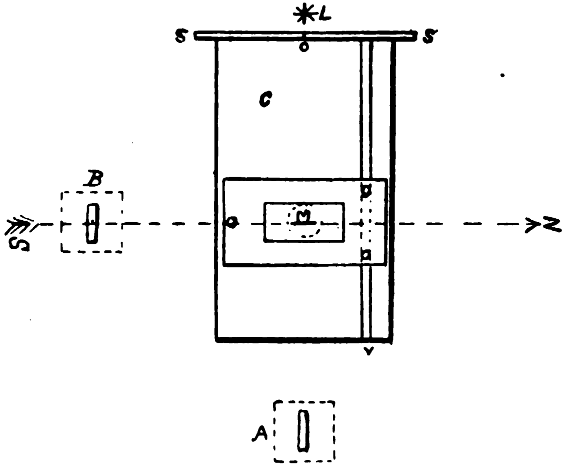


FIG. 12*a*

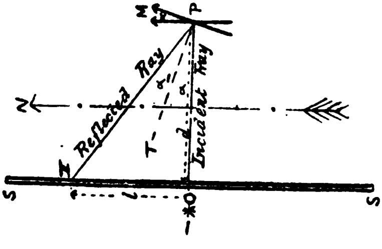


FIG. 12 *b*.

be noticed that the angle between the incident ray O P and the reflected ray P I is marked 2 *a*, or twice the angle of deflection. This is true, since the angular velocity of the spot of light is twice that of the mirror when the mirror is deflected. Thus, if O I $= l$ and O P $= d$,

$$\frac{l}{d} = \tan 2a,$$

from which, by the help of tables of tangents,[1] we can readily determine $\tan a$. An example, using the mirror form of magnetometer, is given below as a final exercise in magnetism.

Experiment 3 B.—**The Determination of H at any Place.**

Apparatus.—A bar magnet of magnetic moment M; the mirror magnetometer with scale, &c., and a box with glass front, in which the magnet is suspended, for counting the oscillations made by the bar magnet.

By the *method of deflection—i.e. by the* A *and* B *tangent positions of Gauss* (Experiment 3 A), we can determine $\frac{M}{H}$, when the magnet is in the *end-on* or *broadside* position, from the equation $\frac{M}{H} = \frac{d^3 \tan a}{2}$ or $d^3 \tan a$; whilst by the *method of oscillations* we can determine M H, when the bar magnet is vibrating at the place where the test is being made, from the equation $MH = \frac{4\pi^2 I}{t^2}$, where I is the moment of inertia of the bar magnet, and t is the time of one oscillation. If we denote the value of $\frac{M}{H}$ by a, and M H by b, then it is obvious that

$$MH \div \frac{M}{H} = \frac{b}{a} \text{ and } H^2 = \frac{b}{a} \therefore H = \sqrt{\frac{b}{a}},$$

from which we see that the determination of H depends upon two distinct observations with the bar magnet—*i.e.* one to determine $\frac{M}{H}$, and the other to determine M H.

As the general principle of making these observations has been described, it will only be necessary to briefly give the results of an actual experiment. It must, however, be remembered that this is a most important test, and that a large number of separate readings must be taken, so as to get a good average result.

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[1] See page 122.

Method of Deflection.—The apparatus was arranged as in fig. 12 *a*, and the mirror was 50 centimetres from the scale. The bar magnet was placed in the ***end-on position***, so that its centre was 40 centimetres distant from the centre of the needle, and the spot of light gave a deflection of 251·45 divisions. On placing the magnet at the same distance on the other side of the needle, the deflection was 260·3 divisions, and each scale division was 1 millimetre.

Calculation of $\frac{M}{H}$:

Magnet to E of needle, 251·45 divisions

$$\therefore \tan 2a_1 = \frac{25{\cdot}145}{50} = {\cdot}5029 \;\therefore\; 2a_1 = 26{\cdot}7^\circ.$$

Magnet to W of needle, 260·3 divisions

$$\therefore \tan 2a_2 = \frac{26{\cdot}03}{50} = {\cdot}5206 \;\therefore\; 2a_2 = 27{\cdot}5^\circ,$$

from which $a_1 = 13^\circ\ 21'$ and $a_2 = 13^\circ\ 45'$.

Let a be the mean of a_1 and a_2, then $a = \frac{1}{2}(a_1 + a_2) = \frac{1}{2}(13^\circ\ 21' + 13^\circ\ 45') = 13^\circ\ 33'$.

Substituting the values determined, in equation $\frac{M}{H} = \frac{d^3}{2} \tan a$, we get

$$\frac{M}{H} = \frac{(40)^3}{2} \tan 13^\circ\ 33' = 32000 \times {\cdot}241 = 7712\ (a).$$

Method of Oscillations.—On suspending the bar magnet exactly in the same place, by means of several silk fibres, the following result was obtained :

Determination of t.

	hrs.	min.	sec.
Time of 0th passage	11	33	54
" " 45th "	11	47	57
Time to make 45 oscillations		14	3

" " " 1 oscillation $= \frac{843}{45} = 18{\cdot}733$ seconds.

Determination of i.

The moment of inertia of a rectangular bar may be calculated from the formula

$$I = w\left(\frac{l^2 + b^2}{12}\right),$$

where w is the mass of the bar in grammes, l its length, and b its breadth both in centimetres. For round bar magnet of radius a

$$I = w\left(\frac{l^2}{12} + \frac{a^2}{4}\right).$$

The bar magnet was rectangular, and $w = 100{\cdot}32$ grammes, $l = 15{\cdot}5$ centimetres, and $b = {\cdot}6$ centimetre, so that

$$I = \frac{100{\cdot}32}{12}\left\{ (15{\cdot}5)^2 + (0{\cdot}6)^2 \right\} = 20\ 11{\cdot}4996.$$

Determination of M H.

$$\text{Since } MH = \frac{4\pi^2 I}{t^2},$$

$$\therefore\ MH = \frac{4 \times (3{\cdot}1416)^2 \times 2011{\cdot}5}{(18{\cdot}733)^2}$$

$$= 226{\cdot}3288\ (b).$$

Determination of H.

$$H = \sqrt{\frac{b}{a}} = \sqrt{\frac{226{\cdot}3288}{7712}}$$

$$= {\cdot}17113.$$

Practical Exercises.—(1) Determine H by the above method; (2) determine M for a bar magnet. Note that $\frac{M}{H} \times MH = M^2$.

ADDITIONAL EXERCISES

Consisting of the practical exercises in Magnetism, given by the Science and Art Department to those taking the Honours Examination in Electricity and Magnetism.

(1) Given a magnet and a magnetometer, determine H by Gauss's method. Determine also the magnetic moment of the magnet. (June 1886 and June 1891.)

(2) Determine, by the method of deflections and oscillations (Gauss's method), the moment of the magnet given to you, and the strength of the magnetic field at the place of experiment. (June 1887.)

(3) Compare the moments of the two magnets supplied to you by the two following methods :—(*a*) by means of the deflections they produce on a suspended magnet; (*b*) by comparing their times of vibration, and determine their moments of inertia by weighing and measurement. (June 1888.)

(4) Measure the moment of a magnet by the deflection method, the value of H being taken = 0·18. (June 1892.)

(5) Determine the ratio of the intensities of the magnetic fields produced by a magnet when placed in different positions within and without an iron tube, to the axis of which the line joining its poles is perpendicular. (June 1892.)

(6) Determine the maximum magnetic moments which can be imparted to a given steel rod by magnetising it (1) by a large permanent magnet, (2) by a given electro-magnet. (June 1893.)

(7) Determine, by the deflection method, the percentage change in the moment of a magnet by heating it from about 15° C. to 100° C. Also determine if the moment is the same as before, when the magnet is again cooled to 15° C. (June 1894.)

(8) Determine the ratio between the moments of two magnets by means of the effects which they produce on the time of oscillation of a given magnet. (June 1894.)

(9) The centre of a magnet revolves in a given circle, so that the magnet always coincides with a radius, and the same pole always points to the centre. Draw a curve indicating the relation between the position of the magnet and the deflection it produces on another magnet placed in a given position. (June 1895.)

(10) Draw a curve showing the ratios of the fields produced by a magnet at a given point, when it is moved from one end of an iron box to the other, to the fields produced at the same point when the magnet occupies the same positions, but is not surrounded by the box. (June 1895.)

(11) Place the magnet supplied to you magnetic east and west, with the north end east, and, by mapping the lines of force in its neighbourhood as disturbed by the earth's field, determine the moment of the magnet, taking H = 0·18 C.G.S. unit. (June 1896.)

Apparatus supplied—magnet, small compass needle, metre rule, drawing paper.

CHAPTER IV

CURRENTS OF ELECTRICITY AND THEIR EFFECTS. GALVANOMETERS

Notes and Definitions.—In arranging the following experiments we shall assume a general knowledge of voltaic cells and the principles underlying the generation of electrical currents, and it will be taken for granted that when we speak of electricity flowing or passing along a conductor, it is known that the physical state of the conductor is changed so long as the current passes, and is, in fact, electrified, and that whilst in this state the space surrounding the wire is also changed and exhibits magnetic properties. It is because electricity itself cannot be seen and treated as a material substance that we are compelled to take advantage of this and other effects, which are produced and accompany the passage of electricity through conductors, to indicate the existence of currents of electricity, and also to measure and compare them. It is well known that currents of electricity possess (1) *magnetic*, (2) *thermal*, and (3) *chemical properties*, or, in other words, that currents of electricity

(1) Set up magnetic fields, magnetise pieces of iron and steel, and deflect compass needles,

(2) Raise the temperature of the conductor through which they flow, and

(3) Decompose compound liquids, and bring from them their constituent elements.

The magnitude of the effects depends upon the strength of the current producing them, and we shall see later that by each of these effects we can determine the strength of a current, and that the results obtained are concordant. Practically the first of these properties, *i.e.* the magnetic, is the one used almost universally in measuring instruments, and for this reason we shall defer the determination of current strength until the connection between electricity and magnetism, and the quantitative relationship existing between currents and the magnetic fields they produce, have been explained. To simplify matters currents of a known strength should be used, and it is assumed that a powerful battery is available for use, and that the current strength is given by means of an ampere-meter or ammeter.

Experiment 4 A.—**Determination of the Intensity of a Magnetic Field due to a Current.**

Apparatus.—A long thick wire stretched horizontally and connected to a powerful battery, and a freely suspended needle as used in the previous experiments.

The character of the magnetic field set up by electricity passing through an indefinitely long straight conductor is shown in fig. 13 *a*, as given by iron filings, whilst in fig. 13 *b* a plan of the field is given when the current is flowing downwards. In this figure the direction of the lines of force are indicated by the arrow-heads, and the deflecting influence upon a freely suspended needle is shown at four points of the fields, and, assuming that the current flowing downward is of 100 amperes strength, the intensity of the field is given for lines one centimetre apart, as calculated from (17) below. It should be noticed that if we combine the relative directions of the current and the lines of force we obtain an identical corkscrew motion, from which we get a simple rule for determining the direc-

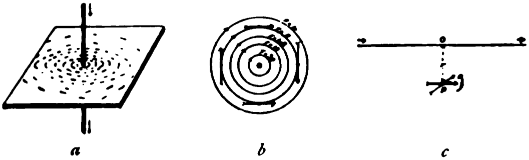

Fig. 13.

tion of a magnetic field produced by a current, known as the corkscrew rule, and introduced by Maxwell.

A current flowing in a conductor sets up magnetic force round the conductor, the direction of which is the same as the direction of rotation of a right-handed corkscrew moving in the same direction as the current.

To measure the intensity of the field at any point it is better to stretch an indefinitely long straight wire horizontally and parallel to a freely suspended needle at a certain distance above it, as in fig. 13 *c*. Both the needle and the conductor are then in the magnetic meridian. When the current is passed through the wire we have two fields at P, one at right angles to the other, and the needle takes up a position coinciding with the resultant direction of the fields. This is another example of the simple tangent law. If F be the strength of the field due to the current at P, the centre of the needle, and H the strength of earth's field at the same point, then

$$\frac{F}{H} = \tan a, \text{ and } F = H \tan a,$$

a being the angle of deflection made by the needle. In this way F may be determined. If $a = 45°$, then $F = H$. It must be remembered that F is the magnetic force at P due to the current, and denotes the force with which a unit magnetic pole would be urged if placed at P, and in this way it measures the strength of the field at P due to the current. As may be inferred, the magnitude of F depends upon (1) the strength of the current, and (2) the distance of the needle from the conductor, and the law connecting F with the current C and the distance r is easily determined mathematically, and is proved experimentally to be

$$F = \frac{C}{\frac{r}{2}} \text{ or } \frac{2C}{r} \quad . \quad . \quad . \quad . \quad (17)$$

C is given in C.G.S. absolute units, since H is always given in those units. We shall show presently that 1 ampere = $\frac{1}{10}$th of the C.G.S. absolute unit of current, so that C absolute units = 10 C amperes. In (17) r is in centimetres, and is measured from the centre of the wire.

Practical Exercises.—(1) Set the long wire (connected t powerful battery) in the meridian at a certain distance above t suspended needle, and note the deflection when different strengt of current are sent along the wire. Prove that F is proportion to the tangent of the angle of deflection, and therefore proportion to C.

(2) Send a fairly strong current (about 5 amperes) along th wire, and vary the distance between the wire and the needle. Prove that F is inversely proportional to r, and $F \times r$ is practically constant.

(3) Arrange the distance, r, and the current so as to get a deflection of 45°. Then $F = H$, and by taking the value of H, as determined in Experiment 3 B, prove that $F = \frac{2C'}{10r}$, where C′ is the current in amperes.

(4) Arrange two wires in same vertical plane, as shown at fig. 14, and send the same current through both wires at the same time, in the directions indicated, and note deflections for different current strengths.

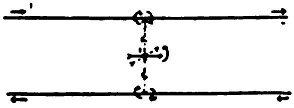

FIG. 14.

In (1), (2), and (3) four readings must be taken by reversing the direction of the current, and by changing the relative position of the needle and the wire, so that a is the mean of four readings.

Arrange the results as follows:

Experiment	C′ in amperes	r	a	tan a	$F = H \tan a$	$F = \frac{2C'}{10r}$	$F \times r$

Exercises.—(1) What deductions may be drawn from the above experiments, and explain any source of error you may have observed?

(2) What effect would a current flowing through a long vertical wire have upon an isolated north magnetic pole if placed in the

field, and what difference would a change in the distance from the wire make in its movements?

(3) Determine the angle of deflection when a current of 4·5 amperes flows through a horizontal wire 9 centimetres distant from a needle placed in a field of ·1731 units strength.

Answer, 30° (approx.).

(4) What would be the deflection if the same current (as in 3) was sent below the needle as well as above (fig. 14), and at the same distance from the needle?

Answer, 49° (approx.).

(5) How may a compass needle be used to determine the direction of a current in a wire, and express as a law the behaviour of the needle when a current is passed parallel to it?

(6) Explain the results obtained in Exercise 4 above.

If the conductor through which the current passes is of short length, then it can be shown that the strength of the field due to the current is proportional to the current, the length of the conductor, and inversely as the square of the distance, that is

$$F = \frac{C\,l}{r^2} \text{ or } \frac{C'\,l}{10\,r^2} \quad . \quad . \quad . \quad . \quad (18)$$

where l is the length of the conductor in centimetres, C the current in absolute units, and C′ the current in amperes. This distinction between the absolute value and practical value of the current will be followed in all cases.

Practical Exercises.—(1) Arrange about 2 centimetres of the conductor parallel to the suspended needle, and note the deflections for different distances between the wire and the needle when a certain current is passed, and tabulate the results. Prove that $C\,l$ is the magnetic value of the element with respect to all points in its equatorial plane. Does the law $F = \frac{m \times m_1}{d^2}$ hold in this case?

(2) Arrange the strength of the current and the distance in the above arrangement, so that the deflection is 45°, and prove the law, $F = \frac{C\,l}{r^2}$ or $\frac{C'\,l}{10\,r^2}$, where C′ is the current in amperes.

If the wire be looped into a circular coil, as in fig. 15, so that

BC, CD, &c., are equal, and by numbering the divisions scale 1, 2, 3, 4, &c., comparative results may be dete directly, since

$$\tan aod = \frac{AD}{AO} = 3\frac{AB}{AO},$$

$$\text{and } \tan aog = \frac{AG}{AO} = \frac{6\,AB}{AO},$$

from which it is evident that

$$\frac{\tan aod}{\tan aog} = \frac{3\,AB}{AO} \div \frac{6\,AB}{AO} = \frac{3}{6} = \frac{1}{2}.$$

A useful addition to the scale is a piece of plane mirror placed ju under the needle, so that the exact position of the needle may b determined.

A very useful form of galvanometer for experimental purposes is one consisting of several distinct coils varying in diameter and in the number of turns. A vertical section of such an instrument is given in fig. 19, in which A and B are two sets of coils of different diameter, that of the coil B being twice the diameter of A. A consists of twenty turns, whilst B consists of two sets of coils of five turns and fifteen turns respectively, the coil of five turns being connected to two terminals 1 and 2, and the other to two terminals 3 and 4, and the coil A to terminals 5 and 6. A little thought will show how we can get 5, 10, 15, and 20 turns respectively from B. When terminals 1 and 2 are used we get five turns, with 3 and 4 fifteen turns, with 1 and 2, and 4 and 3 together we get ten turns, and with 1 and 2, and 3 nd 4 together we get twenty turns, and in this way the effect of

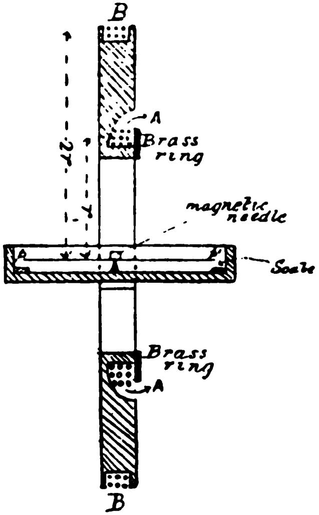

FIG. 19.

varying the number of turns may be determined. By using the twenty turns of A and B we may determine the effect of varying the diameter of the coils.

By combining the two equations $F = H \tan a$, and $F = \frac{2 \pi n C}{r}$ it is evident that

$$\frac{2 \pi n C}{r} = H \tan a,$$

or

$$C = \frac{r}{2 \pi n} H \tan a = G H \tan a \quad . \quad . \quad (22)$$

in which $G = \frac{r}{2 \pi n}$, and we see that using a certain set of coils the only variable quantities in (22) are C and tan a, since $\frac{r}{2 \pi n}$ or G is a constant depending on the dimensions of the coil, and is termed the *true constant* of the galvanometer for that set of coils, and H, the horizontal component of the earth's field, is also constant. Consequently the product of H and $\frac{r}{2 \pi n}$, or K, as it is usually given, is also a constant, known as the *reduction factor* or *working constant* of the galvanometer. It will have been noticed that the values of these constants correspond to the value of C in absolute or C.G.S. units; for practical purposes, however, such as the determination of the current strength, it is convenient to use a working constant, K, which is equal to ten times the product of G and H,

$$\text{since C amperes} = \frac{10 r}{2 \pi n} H \tan a = 10 \, G H \tan a = K \tan a \quad . \quad (23)$$

When this value of K is known, the current in amperes may be determined quite readily.

Practical Exercises.—(1) Send the same strength of current through the 5, 10, 15 and 20 coils of B and note the deflections. If a suitable ammeter be available, vary the current so that the angle of deflection is the same in each case, and in this way determine the effect of varying the number of turns.

(2) Send a current through the twenty turns of A, so as to get a

deflection of, say, 40°, and then send the same current through the twenty turns of B and note the result.

(3) Determine the value of K for each coil by sending such a current that in each case the deflection is 45°. Then $C = K \tan 45°$, or $K = C$.

Note.—The student will be able to vary the current strength by varying the resistance in the circuit, and by making use of an ammeter the principle of the tangent galvanometer is grasped before the instrument is used for making measurements. In the above experiments it is a good plan to change the direction of the current, so as to get the mean of the angles of deflection. The results should be entered up as follows :

Experiment	C from ammeter	r	n	mean deflection	$\tan \alpha$	K calculated	K from $\frac{C}{\tan \alpha}$	$\frac{10r}{2\pi n} H \tan \alpha$

CHAPTER V

EXERCISES WITH TANGENT GALVANOMETER

Notes and Definitions.—Before using a tangent galvanometer for purposes of measurement it will be well to define and explain three fundamental factors present in every active circuit. It is well known that when an insulated substance is electrified it is capable of doing work; in other words, electrification is accompanied by the accumulation of a certain amount of energy, termed *potential energy*, because the body electrified is brought into such a position or condition that in consequence it is capable of doing work. Electrically we say that the body has a certain potential. Potential, then, is an expression of energy, and is measured by the work it can do. In practice we are mostly concerned with electricity in motion or currents of electricity which result whenever we have two points in a conductor at different potentials.

Def.—The difference of potential, or D.P., between two points is that difference in electrical condition which tends to produce a transference of electricity from one point to another.

But we must have something more than D.P. to give a continuous current; for instance, if two bodies are electrified to different potentials and they are connected by means of a wire, we know that a rush of electricity takes place from the body of higher potential to the one of lower potential—that is, we have a discharge or momentary current, and as the result the two bodies are reduced to the same electrical condition. We shall not here inquire into the process of the transformation of any one form of energy into electrical energy, but, taking an ordinary voltaic cell as different resistances inserted in the circuit. These should be arranged to give about 70° as the maximum deflection and 20° as the least.

Practical Exercises.—(1) Conduct the test as explained above and tabulate the results as shown below. Find value of K for each case and place it in column (5).

(2) From the data obtained plot a curve with values of tan a as abscissæ and the corresponding values of $\frac{1}{R_1}$ as ordinates.

(3) Determine the value of K from $C = K \tan 45° = \frac{E}{B + G + R}$ by arranging R to make $a = 45°$. The value of E may be taken from a table[1] giving E.M.F.s of different cells.

Exercises.—(1) Show that the straight line obtained as curve in (2) verifies the tangent law.

(2) Calculate the value of C for each case from $C = K \tan a$.

(3) Prove that C is inversely proportional to R_1.

R from box	(1) R_1 total resistance	Readings		(2) Mean $= a$	(3) Tan a	(4) $R_1 \times \tan a$	(5) K	(6) C Amperes	(7) $\frac{1}{R_1}$
		To right	To left						
20	32	72·5°	73·5°	73°	3·2708	104·6656	·0191	·0625	·03125
25	37	70°	71°	70·5°	2·8239	104·4769	·0191	·0539	·02703
35	47	65·25°	66·25°	65·75°	2·2199	104·3353	·0191	·0424	·02128
40	52	63°	64°	63·5°	2·0057	104·2964	·0191	·0383	·01923
45	57	61°	62°	61·5°	1·8418	104·9826	·0190	·035	·01755
60	72	55°	56°	55·5°	1·4550	104·7600	·0190	·0276	·01391
65	77	53°	54°	53·5°	1·3514	104·0578	·0192	·0260	·01299
85	97	46·5°	47·5°	47°	1·0724	104·9228	·0190	·0204	·01031
100	112	42·5°	43·5°	43°	·9325	104·4400	·0191	·0178	·00893
130	142	36°	37°	36·5°	·7400	105·0800	·0190	·0140	·00704

Experiment 5 B.—**Determination of (1) the Constant of a Tangent Galvanometer and of (2) Current Strength, by the Method of Electrolysis.**

Apparatus.—Tangent galvanometer, battery of constant E.M.F. (Daniell), depositing cell (fig. 22), termed *voltameter*, resistance box, reversing key, chemical balance, and stop watch.

Notes and Definitions.—By the previous experiment (5 A) the strength of a current may be determined when K is known, but a total resistance of the circuit; in other words, the cotangent of the angle of deflection is proportional to the total resistance. By varying R_1, so that we get different values of a, the tangent law may be readily verified. Fig. 20 shows the arrangement of the apparatus for making the test, in which the battery, B, the tangent galvanometer, G, and resistance box, R, are connected in series. R K is a reversing key or commutator for changing the direction of the current in the galvanometer. The construction and method of using this key will be evident from fig. 21.

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[1] See page 119.

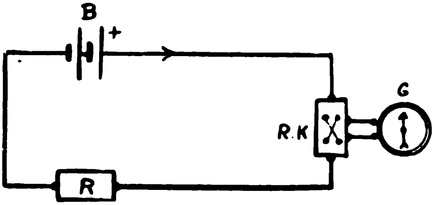
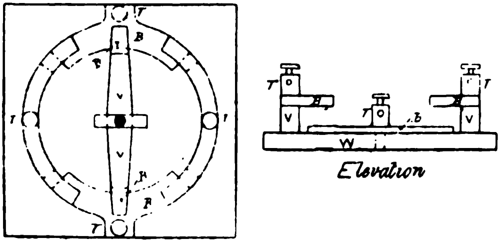


FIG. 20.



Plan

Elevation

FIG. 21.

When using the tangent galvanometer care must be taken to place the coil of the galvanometer perfectly in the magnetic meridian, and when this is the case the pointer should be exactly at zero. In making the test readings of the galvanometer deflections are taken both to the right and left of the zero, for about ten from this deflection and the value of C, K is readily determined, since from (23)

$$K = \frac{C}{\tan a},$$

where a is the average deflection of the tangent galvanometer. Fig. 23 shows a diagram of the connections, in which R K is the reversing key, enabling direct and reversed readings to be taken. Before starting the test it is advisable to determine whether the connections are such as to get the deposit on the cathode. For this purpose it is useful to insert a trial plate of copper in place of the actual cathode for a few minutes. It is also an advantage to arrange the strength of the current, so that the deflection is 45° (see note under Experiment 2 A), and this is obtained by inserting sufficient resistance from the resistance box whilst the trial plate is in position; and if the current should fall off during the test, this resistance may be varied so as to keep the deflection constant, otherwise the average of the angle of deflection must be taken in finding the value of K.

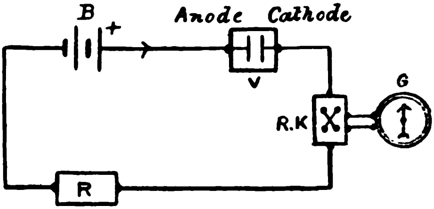


FIG. 23.

Practical Exercises.—(1) Conduct two or three tests as described above, to get a good average value of K for a particular galvanometer. Calculate the current in each case, and tabulate results as shown below.

(2) Plot a curve on squared paper with values of tan a, ranging from tan 30° to tan 60° as abscissæ, and the corresponding values of current required to give these deflections. Use equation $C = K \tan a$, substituting the value of K as determined, and so get

the values of C corresponding to the various values of α. The curve obtained is the calibration curve for the galvanometer, and is useful for determining the current in a circuit.

(3) Determine the current in amperes required: (1) to ring an electric bell, and (2) to enable an electro-magnet to support a small weight.

(4) Calibrate another galvanometer.

Exercises.—(1) What current would deposit 0·38112 of a gramme of copper in one hour? *Answer*, 0·155 of an ampere.

(2) If the constant of a tangent galvanometer be 0·125, determine the angle of deflection during an experiment when 0·7 of a gramme of copper is deposited by a constant current in thirty minutes. *Answer*, 43·5° (approx.)

Method of Tabulating Results and Making Calculations.

Time	Deflections		
	Direct	Reversed	Mean
h. m.			
10 0	Circuit completed		
5			
10			
15			

Battery.
Resistance added . . = ohms
Surface of cathode exposed = square inches
Weight of cathode before . = grammes
" " after . = grammes
Gain = grammes
Mean deflection . . . =
Tan α . . . . . =
Duration of test . . = seconds
Weight of copper per second $= \dfrac{\text{Gain}}{\text{No. of seconds}}$
Strength of current in amperes $= \dfrac{\text{Gain}}{0{\cdot}0003281 \times t}$
Constant of galvanometer $= \dfrac{C}{\tan \alpha} =$

Experiment 5 C.—**Determination of Battery Resistance.**

Apparatus.—Tangent galvanometer of known resistance, several different kinds of cells, resistance box, reversing key, and connecting wires.

The theory of this method, termed Ohm's method, depends upon the application of Ohm's law to a complete circuit, and is very simple. By varying the magnitude of the resistance R from the resistance box we get different values of the current as follows;

$$C = \frac{E}{B + G + R}; \quad C_1 = \frac{E}{B + G + R_1}$$

from which we get

$$\frac{B + G + R_1}{B + G + R} = \frac{C}{C_1}.$$

By applying the tangent law we obtain the value of the ratio $\frac{C}{C_1}$ in terms of the ratio of the tangents of the angles, thus

$$\frac{C}{C_1} = \frac{K \tan a}{K \tan a_1} = \frac{\tan a}{\tan a_1}$$

$$\therefore \quad \frac{B + G + R_1}{B + G + R} = \frac{\tan a}{\tan a_1}$$

from which $B = \frac{R_1 \tan a_1 - R \tan a}{\tan a - \tan a_1} - G$ . . . . . . (29).

This relationship only applies to constant cells, and it must be noted that G is the resistance of the galvanometer and connecting wires. For the reason already referred to before, the best values of the deflections are those between 30° and 60°, and it should be observed that the value of the internal resistance of the battery obtained, whilst being accurate enough for ordinary working conditions, is only approximate, since the internal resistance depends upon the nature of the solution, porous pots and plates used, the area of the plates immersed, and the distance they are apart.

For many purposes this test may be simplified by making $R = 0$, and R_1 so that $a_1 = 45°$, in consequence of which (29) becomes

$$B = \frac{R_1}{\tan a - 1} - G.$$

Another modification, known as *the half-deflection method*, is very useful, and the calculation simplified. The method consists in making R_1 such that $\tan a_1 = \frac{1}{2} \tan a$. Then

$$B = \frac{R_1 \tan a_1 - 2 R \tan a_1}{2 \tan a_1 - \tan a_1} - G = R_1 - (2 R + G).$$

The connections for each of these tests are the same as given in fig. 20.

Practical Exercises.—(1) Determine the internal resistance of a Daniell's, Grove's, and Leclanché cell by the above method. It is a good plan to get several values of a by varying R from zero to 10 ohms, and by taking pairs of observations obtain a good average value of B.

(2) Determine the resistance of a Daniell's cell when (1) one-third filled with solution; (2) two-thirds filled with solution; and (3) full of solution.

(3) Determine the resistance of a bichromate cell with the zinc plate: (1) not amalgamated, (2) amalgamated, in both cases at the commencement of the test and after the cell has been running about twenty minutes.

(4) Compare the resistance of a battery composed of Daniell's cells arranged as follows: (1) one cell only, (2) two cells in series, and (3) two cells in parallel.

Exercise.—(1) Discuss the results obtained in (2), (3), and (4). Tabulate the results as follows:

Experiment	R from box	Deflections			Tan a	B calculated
		Direct	Reversed	Mean		

Experiment 5 D.—**Determination of the Resistance of a Wire.**

Apparatus.—As in 5 C, with several coils of wire of unknown resistances.

If $x =$ unknown resistance of a coil, and a the deflection obtained when it is in series with the tangent galvanometer and battery, as in fig. 20, and a_1 the deflection when the coil of unknown resistance is replaced by a resistance R from the box; then, as before,

$$\frac{\mathrm{B}+\mathrm{G}+x}{\mathrm{B}+\mathrm{G}+\mathrm{R}}=\frac{\tan a_1}{\tan a},$$

$$\text{from which } x=\frac{\tan a_1}{\tan a}(\mathrm{B}+\mathrm{G}+\mathrm{R})-(\mathrm{B}+\mathrm{G}) \quad . \quad . \quad . \quad (30)$$

From this equation it is evident that 'the accuracy of the result will depend upon the correctness of the ratio $\frac{\tan a_1}{\tan a}$,' and that the best result is obtained when $\frac{\tan a_1}{\tan a} = 1$. This suggests the method of making R such that $a_1 = a$, in which case $x = R$. This method is known as ***the method of substitution.***

Should the deflection obtained when the unknown resistance is in circuit be too large, it may be reduced to a convenient amount by adding a resistance, r, from the box. If, on removing the unknown resistance, a resistance R is required from the box to produce the same deflection, it follows that $R = r + x$, or $x = R - r$, and this suggests a method of checking the results obtained by the method of substitution.

Practical Exercises.—(1) Determine the resistances of several coils of wire by the three methods explained above.

(2) Determine the joint resistance of three of the coils connected (1) in series and (2) in multiple arc.

Experiment 5 E.—**Comparison and Determination of Electro-motive Forces.**

Apparatus.—Same as in 5 C.

$$\left.\begin{aligned} \text{Since } C &= \frac{E_1}{B+G+R_1} = K \tan a_1 \\ C_1 &= \frac{E_2}{B+G+R_2} = K \tan a_2 \end{aligned}\right\} \therefore \frac{E_1}{E_2} = \frac{(B+G+R_1)\tan a_1}{(B+G+R_2)\tan a_2} \quad . \quad (31)$$

where E_1 and E_2 are the E.M.F.s of the two batteries under test, and by suitably arranging R_1 and R_2 the following modifications result:

$$\begin{aligned} \frac{E_1}{E_2} &= \frac{B+G+R_1}{B+G+R_2}, \text{ if } a_1 = a_2 \\ &= \frac{\tan a_1}{\tan a_2}, \text{ if } B+G+R_1 = B+G+R_2. \end{aligned}$$

And by connecting the two batteries in series we get

$$K \tan a_1 = \frac{E_1 + E_2}{B+G+R} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (a)$$

When connected so that the E.M.F. of one opposes that of the other, and keeping the total resistance of the circuit constant, we get

$$K \tan a_2 = \frac{E_1 - E_2}{B + G + R} \quad . \quad . \quad . \quad . \quad . \quad (\beta)$$

From (a) and (β) we get

$$\frac{E_1 + E_2}{E_1 - E_2} = \frac{\tan a_1}{\tan a_2}$$

and

$$\frac{E_1}{E_2} = \frac{\tan a_1 + \tan a_2}{\tan a_1 - \tan a_2} \quad . \quad . \quad . \quad . \quad . \quad . \quad (32)$$

This is the '*sum and difference method.*'

Practical Exercises.—(1) Compare the E.M.F. of a Grove's, bichromate, and Leclanché cell with that of a Daniell's.

(2) With each cell get a_1 when the total resistance in the circuit is R, and a_2 when a resistance r is added, and determine the E.M.F. of the three first-named cells from $E = \frac{K \, . \, r \, . \tan a_1 \tan a_2}{\tan a_1 - \tan a_2} \div 10^8$. Compare this with value obtained in (1), assuming E.M.F. of Daniell's cell to be 1 volt.

CHAPTER VI

MIRROR GALVANOMETER AND SIMPLE MEASUREMENTS

Notes and Definitions.—The tangent galvanometer, though a very useful instrument in many instances, is not sufficiently sensitive for the measurement of very feeble currents. The distance between the needle and the coils, the weight of the needle and pointer, and the friction between the magnet and pivot, tending to diminish the free movement of the needle, will not permit of extreme sensitiveness with this form of galvanometer. Another objection is the difficulty of accurately reading small changes in the deflection of the needle. To obviate these objections, Lord Kelvin introduced the method of attaching one or more very small magnetic needles to a light mirror of silvered glass, suspended by a fibre of silk at the centre of a large number of coils of wire of small dimensions, thus ensuring small and very light moving parts. By using a reflected beam of light as a pointer, it is possible to indicate the slightest movement of the needle by means of a spot of light on a scale placed some distance away. In this way small deviations of the needle are magnified a large number of times. The method of doing this will be understood from the sketch of the arrangement shown in fig. 24, which shows how the light from a lamp is thrown upon the mirror by means of a lens, L, and then reflected back to the scale as a spot of light. The essential parts of a galvanometer are:

(1) A large number of coils of wire close to the needle;

(2) A freely suspended needle or needles strongly magnetised and

(3) A weak controlling force.

The first condition is fulfilled by using very fine wire for the coils, the mean diameter of which is very much smaller than that of an ordinary tangent galvanometer. As previously pointed out, the earth's directive influence is the controlling force, and this may be materially diminished by introducing a second magnet or set of needles mounted so as to be parallel to the suspended magnetic needle or needles, and to move freely with them about the same vertical axis. The distance between the sets of needles is small, and their N poles are reversed, thus forming an *astatic combination.* With such a system of needles, the earth's action is very nearly neutralised. Usually one set of needles is placed at the centre of the coil, and the other just outside, as shown in figs. 25 *a* and 26. With this arrangement the deviation produced by a very small deflecting force is materially increased, on account of (1) the controlling force being small, and (2) the second set of needles being deflected in the same direction by the adjacent part of the coil. In very delicate galvanometers of this type both sets

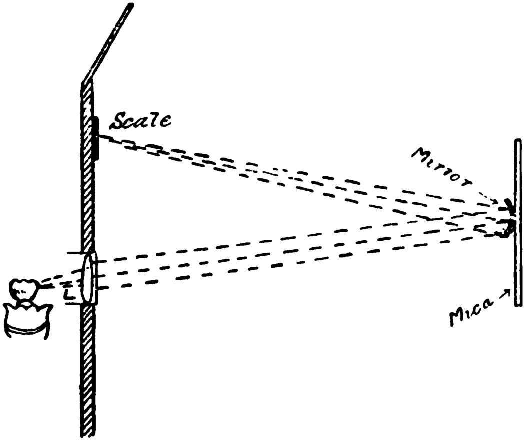


FIG. 24.

of needles are enclosed, as shown in fig. 25 *b*, from whic seen that two coils are used in which the same current in opposite directions. In these instruments the ne mirror are attached to a thin, narrow sheet of mica.

When some practical acquaintance has been made

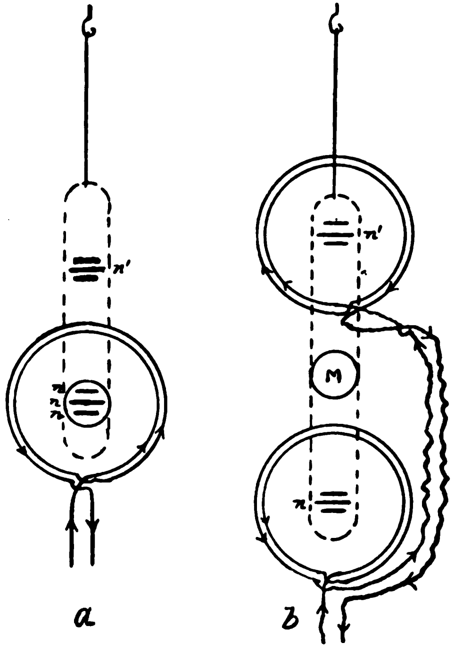


FIG. 25.

mirror galvanometer, the student will discover how minute currents used with this galvanometer are, and it is a decided adv tage that the deflections of the needles are small and do not of exceed 10° on either side of zero. It is in consequence of this t the *circular measure of the angle of deflection* may, without int

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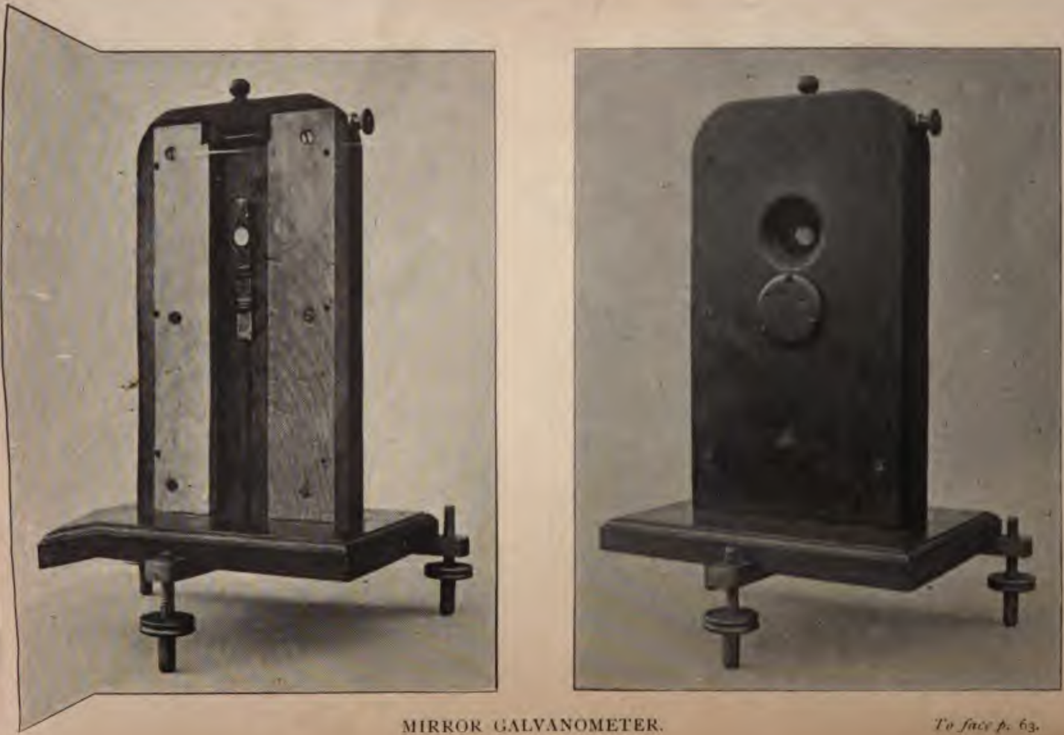

MIRROR GALVANOMETER.

To face p. 63.

ducing any serious error, be taken as being equal to the *tangent of the angle of deflection*.

Theoretically,

$$C = K \tan a,$$

but practically

$$C = K \times a,$$

from which we get the law of the mirror galvanometer, i.e. *the current producing the deviation is proportional to the angle of deflection.* An extremely useful form of the mirror or reflecting galvanometer is shown in detail in fig. 26, from which the construction is obvious. If the moving parts oscillate to any great extent, it is advisable to attach a light vane of aluminium, so that the movements are resisted by the friction of the air and vane.

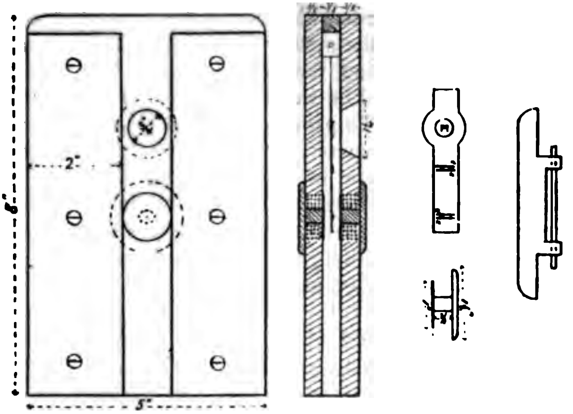

FIG. 26.

It will be well to point out here that perfect adjustment of the galvanometer and accessories is essential if reliable results are to be obtained, and the following precautions must be attended to when fixing up the instruments:

(1) The galvanometer should be placed on a rigid support, the

plane of the coils being in the magnetic meridian, with the scale placed parallel to the galvanometer at a distance equal to the focal length of the mirror.

(2) The flame of the lamp, the zero division of the scale, and the centre of the mirror must be in the same vertical plane. The slit through which the light passes from the lamp should be a little below the centre of the mirror, the general arrangement being shown in fig. 24.

(3) The galvanometer should be carefully levelled so that the needle swings freely, and it is important that the suspended parts be not influenced by torsion of the thread.

Great care is also needed when using the mirror galvanometer, since the suspension of the moving parts is so delicate that there is some danger of breaking the fibre of silk should the needle be moved violently, as would be the case if too great a current were sent through the coils. To prevent this, and also to diminish the sensibility of the galvanometer, it is usual to shunt the galvanometer with a short piece of wire when making preliminary observations. The wire forming the shunt is connected across the terminals of the galvanometer, and carries a large proportion of the current. When making the actual test the shunt should be removed, except in the cases mentioned.

Experiment 6 A.—**Proof of Ohm's Law.** (First Method.)

Apparatus.—Mirror galvanometer and its accessories, several constant cells, a metre length of No. 30 German silver wire stretched upon a metre scale, and soldered to copper plates with terminals attached, as shown in fig. 27, a resistance box or coil of wire of several thousand ohms resistance, and a reversing key.

From $C = \frac{E}{R}$, the usual algebraic statement of Ohm's law, it is evident that if C be constant throughout a set of tests in which E is made to vary, then R must vary in the same proportion as E. A very ready method of obtaining a variation in the magnitude of E is to tap a wire of constant cross-section through which a constant current is passing at different points, and if Ohm's law be true, the ***drop in volts*** along the wire should be uniform and proportional to the resistance between the points. For instance, with the arrangement shown in fig. 27 we may assume that a constant difference of potential is maintained between the terminals A and C by the battery B. And since the galvanometer circuit is a simple branch circuit the current passing through the galvanometer will depend upon the D.P. between the points at which it joins the main circuit. Thus, if contact is made at A and D, as shown in the figure, the pressure sending the current through the galvanometer circuit is given by the D.P. between A and D, and if A D is 40 centimetres long, the D.P. between A and D should be $\frac{4}{10}e$, or $\cdot 4\,e$, e being the D.P. between A and C; and similarly the D.P. between any other two points along A C will be the same fraction of e as the distance between the two points is of the whole distance A C. And since the resistance of a conductor is proportional to the

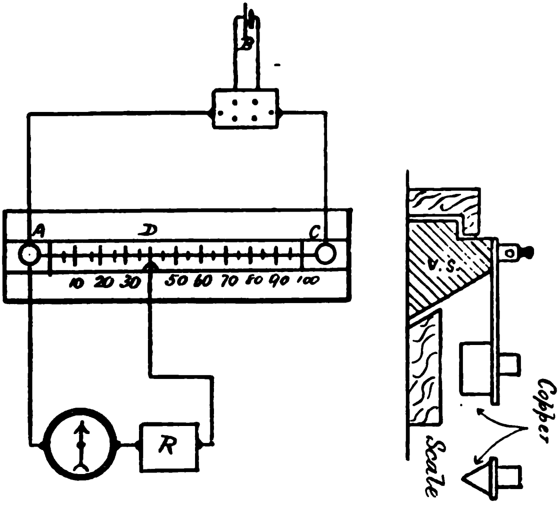

FIG. 27.

being used for the *ratio arms* of the bridge. This form of bridge is easily and cheaply constructed, and if used in conjunction with reliable standard coils permits of great accuracy. Three connecting pieces, A, C, E, of stout copper bar (the two former being right-angle pieces), to each of which binding screws are soldered, as indicated by the small circles, are firmly fastened to a board about 42 inches long and 9 inches wide, the inner edges of the right-angle pieces being exactly one metre apart. The German silver or platinoid wire is tightly stretched and soldered between A and C, so as to be exactly one metre in length. Upon the board and under the wire is screwed a boxwood scale one metre in length and divided into centimetres and millimetres. The same letters are used as in figs. 31 and 32, and contact is made with the metre wire by means of a sliding key, K_2, which is free to move from A to C, so that the segments into which the metre wire is divided by the key at F form the two resistances, P and Q. The construction of the key is shown in fig. 34. In using this form of bridge, the ratio $\frac{P}{Q}$ is varied by means of the key until balance is obtained; the actual position of F depends upon the ratio of R to S, which are two resistance coils inserted in the gaps *a* and *b*. The point F divides the metre wire into two sections

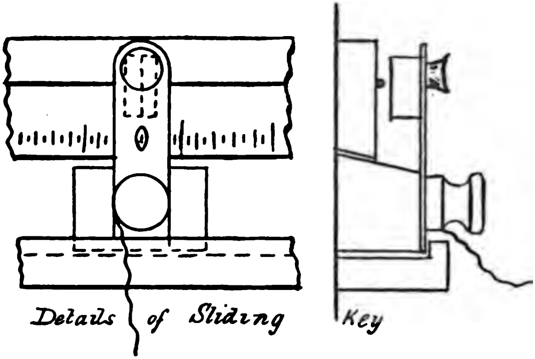

FIG. 34.

l_p and l_q millimetres in length, and since $l_p + l_q = 1{,}000$ millimetres, the ratio $\frac{P}{Q}$ may be written $\frac{l_p}{l_q}$ or $\frac{l_p}{1000 - l_p}$, resistance being proportional to length.

Experiment 7 A.—**Comparison of Resistances and Proof of Laws.**

Apparatus.—Mirror galvanometer and accessories, metre bridge, standard resistance coils and samples of wires, one Daniell's cell.

The connections, as shown in fig. 33, correspond to the arrangement of conductors shown in figs. 31 and 32, and the experiment consists in finding the position of F on the bridge wire. In practice it is advisable to insert a key, K_1, in the battery circuit, so that the battery power be not wasted, and also to diminish the sensibility of the galvanometer by shunting it when making the rough test. At the commencement make contact with the metre wire by means of K_2 near to one end, and a deflection to the right (say) will be obtained ; on moving the key to the other end of the wire the deflection should be to the left, provided the connections are right. Somewhere between these two points a position may be found which gives no deflection. This is found *roughly* with the shunt *present*, and *accurately* with the shunt *removed*, and the student should accustom himself from the commencement to look upon deflections to the right as indicating too much or too little as the case may be, and deflections to the left as the reverse. Let the position of equilibrium be l_p mm. from A, then we shall have

$$\frac{R}{S} = \frac{P}{Q} = \frac{l_p}{1000 - l_p},$$

and if $l_p = 455$ mm.

$$\frac{R}{S} = \frac{455}{1000 - 455} = \frac{455}{545} = \frac{91}{109} = \cdot 835$$

$$\therefore R = S \times \cdot 835.$$

The Metre Bridge is most sensitive when R and S are approximately equal, in other words, when F nearly bisects the metre wire. It is also essential that the conductors placed in the gaps *a* and *b* should have no self-induction, to avoid which the wire is doubled on itself and wound so as to form a coil, as shown in fig. 37. When the actual resistance, R, of a conductor is required, a standard resistance coil, made of German silver, or platinoid, and of known resistance, replaces S, and is inserted in the gap *b*. In all cases the battery key should be closed first, and the galvanometer key afterwards.

Practical Exercises.—(1) Take two lengths of No. 24 German silver wire, $4\frac{1}{2}$ and $5\frac{1}{2}$ feet long respectively, and insert them in the two gaps *a* and *b*. Find the position of equilibrium on the bridge, and prove that resistance is proportional to length. Reverse the positions of the wires and check the result.

(2) Replace each of the above wires in turn by a standard one-ohm coil, and find the resistance of each in ohms.

(3) Connect the two wires in *series*, and determine the joint resistance by comparison with a standard two-ohm coil. Compare the result with that obtained in (2).

(4) Make another spiral of the same wire $5\frac{1}{2}$ feet in length, and connect it in multiple arc with the one of equal length. Compare them with the $4\frac{1}{2}$-feet spiral, and prove that the joint resistance of two wires of equal resistance connected in multiple arc is half the resistance of the single wire.

(5) Connect one of the $5\frac{1}{2}$-feet spirals in parallel with the $4\frac{1}{2}$-feet spiral, and determine their joint resistance by comparison with a standard one-ohm coil. Prove that $\frac{1}{R} = \frac{1}{r_1} + \frac{1}{r_2}$ or $R = \frac{r_1 \times r_2}{r_1 + r_2}$.

(6) Compare the resistances of two copper wires of different lengths and diameters, and prove that the relations

$$R \propto \frac{\text{length}}{\text{square of diameter}} \text{ and } R \propto \frac{\text{length}}{\text{cross-sectional area}} \text{ are correct.}$$

(7) Determine the relative resistances of several wires of equal length and diameter, but made of different materials, by comparing them with a copper wire of the same dimensions. Calling the resistance of the copper wire unity, determine the relative specific resistances of the wires.

Tabulate the results as follows :

Experiment	Ratio arms of bridge		Value of S	Value of R determined	Description of wire
	P in mm.	Q in mm.			

Experiment 7 B.—**Accurate Determination of Resistances by Metre Bridge and the Manufacture of Coils.**

Apparatus.—As above.

The form of metre bridge shown in fig. 35 permits of some simple modifications, in consequence of which we are enabled to obtain more accurate results by eliminating the following sources of error :

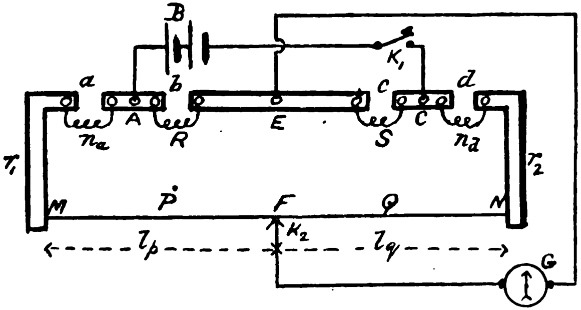

FIG. 35.

(1) The resistances of the right angle pieces and those produced by imperfect soldering of the metre wire to them.

(2) Errors due to the difficulty of reading the exact position of the key on the metre wire.

From the figure it will be observed that there are four gaps, *a*, *b*, *c*, and *d*, instead of two, and that if the coils R and S are [illegible] and *a* and *d* bridged over by thick conduct [illegible] the battery and galvanometer being connected as sho [illegible] The bridge is identical with the one used above, but as it provi [illegible] means of taking an extra reading a more reliable result is o [illegible] Then with the coil of unknown resistance, R in *b*, and th [illegible] let [illegible] be l_Q millimetres from the end M, an [illegible] on interchanging R and S let l_P millimetres be the distance of [illegible] then

$$\frac{R}{S}=\frac{l_Q}{1000-l_Q}\text{ and }\frac{R}{S}=\frac{1000-l_P}{l_P}.$$

By adding the numerators and denominators together we get

$$\frac{R}{S}=\frac{1000+l_Q-l_P}{1000-l_Q+l_P}=\frac{1000+d}{1000-d}\quad.\quad.\quad.\quad.\quad(34)$$

where *d*, the difference in the bridge readings, is a small quantity. If r_1 and r_2—in terms of a division of the metre wire—denote the resistances of the end pieces, then the above equations become

$$\frac{R}{S}=\frac{l_Q+r_1}{1000-l_Q+r_2}\text{ and }\frac{R}{S}=\frac{1000-l_P+r_2}{l_P+r_1}$$

$$\text{and }\therefore\frac{R}{S}=\frac{1000+r_1+r_2+d}{1000+r_1+r_2-d}\quad.\quad.\quad.\quad.\quad.\quad(35)$$

r_1 and r_2 may be determined by several methods, and should be marked on the board for future use. When the resistance R is known to be very nearly equal to S, the sensibility of the bridge may be increased by increasing the length of the bridge wire. This is attained by inserting in the gaps *a* and *d* two additional coils of wire, the coil at *a* having a resistance equal to n_a millimetres of the bridge wire, and that at *d* a resistance equal to n_d millimetres, then equation (35) becomes

$$\frac{R}{S}=\frac{1000+n_a+n_d+r_1+r_2+d}{1000+n_a+n_d+r_1+r_2-d}=\frac{a+d}{a-d}=1+\frac{2d}{a}\quad.\quad.\quad.\quad(36)$$

where $a=1000+n_a+n_d+r_1+r_2$.

These modifications may, with advantage, be applied to the testing of standard resistance coils, and to the adjustment of lengths of wire, so that they may have a definite resistance, as in the manufacture of standard coils for rough tests. The wire used for this purpose is of German silver, well insulated by two layers of silk. To be serviceable the wire is wound—doubled on itself—upon a wooden bobbin, well soaked in paraffin wax. The two free ends should be connected to two terminals securely screwed into the bobbins. The adjustment in the resistance is made at the centre, which is left free for this purpose, care being taken to reduce the resistance gradually by soldering the double part together as required. When finished the coil should be covered with paraffin wax and wrapped with tape. In commencing the manufacture of a coil, one metre length of the right sized wire is cut off, and its resistance accurately measured. The proper length of wire required for the coil is then calculated, allowance being made for adjustment. For 1 and 2 ohms coils use No. 18 wire; for 5 ohms, No. 19; for 10 and 20 ohms, No. 21.

Practical Exercises.—Manufacture coils having respectively 1, 2, 5, and 10 ohms resistance by comparison with standard coils as explained above.

Post Office Bridge.—The second form of Wheatstone's Bridge is the post-office pattern, which practically consists of a box containing twenty-two standard coils and connections arranged so as to form a very compact and at the same time complete bridge. A plan of the arrangement is shown in fig. 36, and the method of fixing the coils in fig. 37. The free ends of the coils, which are made of platinum-silver, are soldered to solid brass pieces fixed to a block of insulating material, and between the adjacent brass pieces there is a carefully formed conical recess, in which a stout conical brass plug with an insulating handle is inserted. When the plugs fit the holes tightly, the resistance coils are practically short-circuited, and to place any coil in circuit the corresponding plug is removed. With this pattern of bridge the proportional or ratio arms, S and Q, each consists of three coils of 1,000, 100, and 10 ohms resistance respectively, and form the top row in the box, the ratio $\frac{S}{Q}$ is maintained constant and equal to unity, $\frac{1}{10}$ or $\frac{1}{100}$, according to the degree of accuracy desired, and balance a number by varying the value of R. The rheostat arm, P, consists of a series of coils having the following resistances: 1, 2, 2,

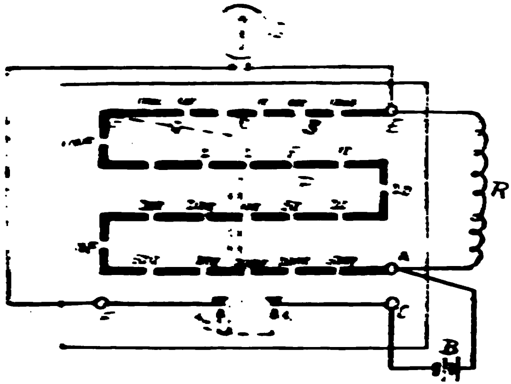

Fig. 36.

5; 10, 20, 20, 50; 100, 200, 200, 500; . . . up to 5,000 ohms, from which any desired value from 1 to 11,110 ohms may be obtained by removing the proper plugs: thus 376 would be made up as follows: 200 + 100 + 50 + 20 + 5 + 1. When the plug marked INF is removed, infinite resistance is introduced, and that part of the circuit is completely broken. The battery and galvanometer are connected to the terminals A and C, and E and F respectively; the keys K_1 and K_2 when closed connect the pieces C and C_1 and F and F_1 together by means of stout pieces of wires placed inside, and indicated by the dotted lines. The wire of unknown resistance, which has to be determined, is inserted between the terminals A and E, and the student will experience no difficulty in following

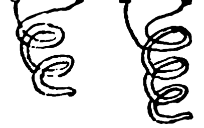

Fig. 37.

the connections in this form of bridge if figs. 32 and 36 be carefully studied together. The order of procedure in determining the resistance of a wire is briefly as follows: With the galvanometer shunted determine the value of R to the nearest whole number by taking $S = Q = 10$. Then to the first decimal place by taking $Q = 100$ and $S = 10$, and finally to the second decimal place by taking $Q = 1{,}000$ and $S = 10$. When this value has been obtained, it is highly probable that a deflection is given by the galvanometer, in which case the exact resistance may be found by interpolation as follows: Let r_1 be the resistance when a deflection of d_1 divisions to the left indicates too little, and $(r_1 + \cdot 01)$ when a deflection d_2 divisions to the right indicates too much; consequently ·01 produces a difference of $(d_1 + d_2)$ divisions, from which it is obvious that balance would be obtained when

$$R = r_1 + \frac{d_1}{d_1 + d_2} \times \cdot 01.$$

To take an example: The resistance of a coil was found to be between 5·74 and 5·75 ohms; when too little there was a deflection of 10 divisions to the left, and 15 divisions to the right when P was 575. Consequently

$$R = 5\cdot 74 + \frac{10}{25} \times \cdot 01 = 5\cdot 74 + \cdot 004 = 5\cdot 744 \text{ ohms.}$$

It is important to notice that loose contact with the plugs introduces errors, and it is necessary before making a test to see that the plugs are put in firmly, and that the brass pieces and plugs are free from dirt or grease.

The student will now be in a position to compare the results obtained with the metre bridge and the post-office bridge, and the following practical exercises are framed so as to give practice with both forms. It must, however, be remembered that the resistances as given by the box are only correct for one temperature, and the temperature of the room should be noted when a test is being made. The effect of variation of temperature upon the electrical resistance of a conductor will be apparent when the experiment (3) 7 C has been performed. In addition to its use as a bridge the post-office box is frequently used as a *resistance* box.

Experiment 7 C.—**Determination of Resistances, Specific Resistance and Variation of Resistance with Temperature.**

Apparatus.—Mirror galvanometer and accessories, battery, metre bridge, post-office bridge, thermometer and heating apparatus, resistance coils previously manufactured.

Practical Exercises.—(1) Test the resistances of the manufactured coils by the post-office bridge.

(2) Determine exactly the resistance of a sample of wire two metres in length, by both bridges, and enter the results as follows:

Experiment	Ratio arms		Rheostat arm P =	Value of R determined	Deflection for final adjustment	Description of wire	Temperature
	S=	Q=					

(3) Insert the above sample of wire in an oil bath; the temperature may be varied by using a spirit lamp. Determine the resistance at the temperature of the room, and at every 10° increase of temperature up to 100° C. Allow the bath to cool down slowly, and measure the resistances at the same temperatures as before. Stir the oil well when taking the temperature. Enter the results as follows:

Experiment	Temperature	Resistance		Temperature coefficient
		Heating	Cooling	

Exercises.—1. Calculate the specific resistance of the sample of wire used in (2) from the results obtained, and from the formula $R = \frac{\sigma . l}{A}$, where R = resistance in ohms, σ = specific resistance = resistance of centimetre cube, l = length in centimetres, A = area of cross section in square centimetres = $0{\cdot}7854\,d^2$ (d = diameter).

2. From the increase of resistance determined in (3) calculate the mean percentage change of resistance per 1° C., both for heating and cooling.

3. Plot two curves on the same sheet of squared paper, one for heating and one for cooling, taking temperatures as abscissæ and resistances as ordinates. The value got for the percentage variation from a mean curve should correspond to the mean of the values found in (2).

CHAPTER VIII

SHUNTS, MEASUREMENTS OF E.M.F.s, HEATING EFFECTS, AND THERMAL CURRENTS

Shunts.—*Notes and Definitions.*—Attention has already been drawn to the fact that it is often necessary to use shunts with such delicate instruments as mirror galvanometers, with the result, as the student will have observed, that

(1) The sensibility of the galvanometer is diminished, and consequently the range of the instrument is increased; and

(2) The galvanometer is protected from injury.

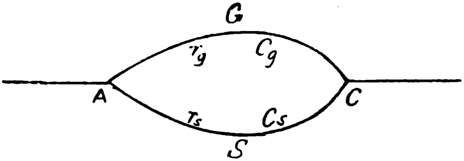

FIG. 38.

Def.—A shunt is any conductor in which there is no source of E.M.F. which serves as a by-path to another conductor.

Now, since the current passing through a shunted galvanometer is less than that which would pass with the shunt removed, but otherwise under exactly similar conditions, it is evident that the actual function of a shunt is to reduce the difference of potential at the galvanometer terminals. When a galvanometer is shunted the arrangement forms a simple divided circuit, and the relative strengths of the currents through the shunt and galvanometer may be readily determined as follows: In fig. 38 let the two conductors forming the divided circuit between A and C represent a shunted galvanometer, the branch A G C of resistance r_g representing the galvanometer, and the branch A S C of resistance r_s the shunt. If E be the D.P. between A and C, the terminals of the galvanometer, and C, C_g, and C_s the currents in the main circuit, galvanometer, and shunt respectively, then

$$E = C_g \times r_g = C_s \times r_s$$

and

$$\frac{C_g}{C_s} = \frac{r_s}{r_g} \quad . \quad . \quad . \quad . \quad . \quad . \quad (37)$$

or, in words, *the relative strengths of the currents in the galvanometer and shunt are inversely proportional to their resistances.*

Again, since $C = C_g + C_s$ and $C_s = C_g \times \frac{r_g}{r_s}$

$$\therefore\ C = C_g + C_g \times \frac{r_g}{r_s} = C_g\left(1 + \frac{r_g}{r_s}\right) = C_g\left(\frac{r_g + r_s}{r_s}\right)$$

and

$$\left.\begin{aligned} C_g &= \frac{r_s}{r_g + r_s} \times C \\ C_s &= \frac{r_g}{r_g + r_s} \times C \end{aligned}\right\} \quad . \quad . \quad . \quad (38)$$

similarly

From these results it is evident that the current through the galvanometer may be varied within wide limits by varying the resistance, r_s, of the shunt, and it may be arranged so that the galvanometer current shall be any desired fraction of the main current. For instance,

If $r_s = r_g$, then $C_g = \frac{1}{2}\ C$ by substitution in $C_g = \frac{r_s}{r_g + r_s} \times C$;

„ $r_s = \frac{1}{2}\ r_g$ „ $C_g = \frac{1}{3}\ C$;

„ $r_s = \frac{1}{n}\ r_g$ „ $C_g = \frac{1}{n + 1}\ C$;

„ $r_s = \frac{1}{n - 1}\ r_g$ „ $C_g = \frac{1}{n}\ C$ . . . . (39)

In all cases in practice where it is necessary to determine the current through the galvanometer, it is usual to use shunt boxes containing resistance coils, such that n may be 10 or some power of 10. To do this r_s must be related to r_g, as follows :

When $n = 10$, then $r_s = \frac{r_g}{10 - 1} = \frac{1}{9} r_g$;

" $n = 100$, " $r_s = \frac{1}{99} r_g$;

" $n = 1{,}000$, " $r_s = \frac{1}{999} r_g$.

Experiment 8 A.—**To Verify the Relation** $C_g : C_s = r_s : r_g$.

Apparatus.—Mirror galvanometer and accessories, one or two constant cells, post-office box, and reversing key.

The results of this experiment will depend to a great extent upon the constancy of the battery and upon the total resistance of the circuit being maintained the same whilst the resistance of the shunt is varied. The arrangement of the apparatus shown in fig. 39 is suitable for cases where the galvanometer resistance is from 10 to 20 ohms. The battery is connected between the terminals E and C of the post-office box, and the galvanometer and reversing key are connected between the terminals A and C, so that B E A G C is the main circuit, and the portion of the box between A and C may be used as a shunt to the galvanometer. If a high resistance R (about 100 times that of the galvanometer) be inserted in the main circuit, and the battery remain constant, it may easily be proved that very little variation will take place in the strength of the current in the main circuit, although the shunt resistance r_s be varied between fairly wide limits. By removing the infinity plug in the shunt branch, r_s becomes infinite, or, in other words, the shunt circuit is broken, and the deflection obtained is a measure of the current in the main circuit throughout the experiment. K is a reversing key, and by inserting a tangent galvanometer, G_1, in the battery circuit, any variation in the current may be detected at once.

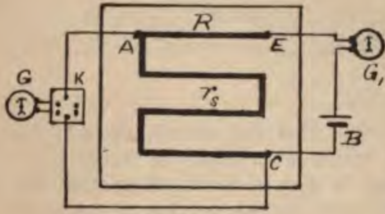

FIG. 39.

Practical Exercises.—(1) Connect the apparatus as shown in fig. 39, and note the galvanometer deflections, both direct and reversed, when the following resistances form the shunt; infinity, 20, 10, 5, 4, 2, and 1 ohms. Tabulate the results as follows:

Experiment	Value of r_s	Deflections		Mean, representing value of current through galvanometer	c_g from $c_g = \frac{r_s}{r_g + r_s} c$	Value of c determined with tangent galvanometer
		Direct	Reversed			

(2) Plot a curve with values of r_s as abscissæ and deflections as ordinates, and prove that $c_g : c_s = r_s : r_g$.

Exercises.—(1) Prove that if a shunt of resistance $r_s = \frac{1}{n-1} r_g$ be applied to a galvanometer of resistance r_g in a circuit of low resistance, that compensation resistance equal to $\frac{n-1}{n} r_g$ must be added to the main circuit to maintain a constant current in that circuit.

(2) A galvanometer of 1,245 ohms resistance is shunted so that only $\frac{1}{250}$th of the total current passes through the galvanometer; what must be the resistance of the shunt, and what is the diminution in the resistance of the circuit by using the shunt? If 124·5 amperes pass through the shunt, what is the strength of the main current?

Answers: 5 ohms; 1,240·02 ohms; 125 amperes.

(3) Calculate from the results obtained the values of r_s for a shunt-box for the galvanometer used, so that $\frac{1}{10}$, $\frac{1}{100}$, or $\frac{1}{1000}$ of the total current may pass through the galvanometer, as desired.

Experiment 8 B.—**Comparison and Measurement of E.M.F.s of Cells.**

Apparatus.—Mirror galvanometer and accessories, several different cells, high resistance and connecting wires.

others may be deduced, which form the basis of measurements depending upon the fall of potential along a wire. For instance,

since $$\frac{E}{R} = \frac{e_1}{r_1}$$

it follows that $$\frac{e_1}{E} = \frac{r_1}{R} \qquad \text{. . . . . . (43)}$$

that is, *the* D.P. *between any two points in a circuit is the same proportion of the* E.M.F. (*of the circuit*) *as the resistance between the points is of the total resistance of the circuit.* Again,

since $$E = C\,R,\ e_1 = C\,r_1,\ e_2 = C\,r_2,\ e_3 = C\,r_3,$$

∴ drop in volts = ohmage × amperage,

and $$\frac{e_1}{e_2} = \frac{r_1}{r_2} \qquad \text{. . . . . (44)}$$

Ohmage refers to the resistance between the two points under consideration. These relationships may be verified by using a galvanometer, having a resistance of 1,000 ohms or more, connected to a post-office box, as in Experiment 8 A, or, better still, by using the high resistance galvanometer with the metre wire of Experiment 6 A; in fact, the two Experiments 6 A and 8 C are identical, since the relationships just given are direct consequences of Ohm's Law. A constant battery is connected to the ends of the metre wire, and the D.P.s between different points along the wire are measured by the deflections of the high-resistance galvanometer.

Practical Exercises.—(1) With the high-resistance galvanometer connected as in Experiment 6 A, observe the deflections when 20, 40, 50, and 75 centimetres of the metre wire form the boundary of the galvanometer circuit, and prove the relationship $\frac{e_1}{e_2} = \frac{r_1}{r_2}$.

(2) With the high-resistance galvanometer and post-office box connected as in 8 A (see fig. 39), observe the deflections, both direct and reversed, when 1^{ω}, 2^{ω}, 3^{ω}, 4^{ω}, and 5^{ω} are inserted between A and C, (1) with 1,000 ohms and (2) 2,000 ohms inserted between E and A.

Tabulate the results as follows :

Experiment	Resistance between A and C	Deflections			Ratio of pairs of resistances	Ratio of corresponding pairs of deflections
		Direct	Reversed	Mean		

(3) Plot a curve, taking values of resistances as abscissæ and the deflections as ordinates. The curve should be nearly a straight line.

Experiment 8 D.—**Measurement of E.M.F. with Potentiometer.**

Apparatus.—As in Experiment 8 C, with several cells to be tested.

By modifying experiment (1) of 8 C we can compare and measure the E.M.F. of cells, and for this reason the metre wire is known as a *potentiometer*. When in use the ends of the wire are maintained at a constant D.P., and it is an advantage to use two sliding keys of the kind shown in fig. 27. The connections for the measurement of E.M.F. are shown in fig. 41, in which A D is the potentiometer wire, which is divided into 1,000 parts by the millimetre divisions of the scale. B is an accumulator cell or two Daniell's cells, by means of which the D.P. between A and D is maintained constant. Two cells, C_1 and C_2, are connected to one terminal of a high-resistance galvanometer and to the keys K_1 and

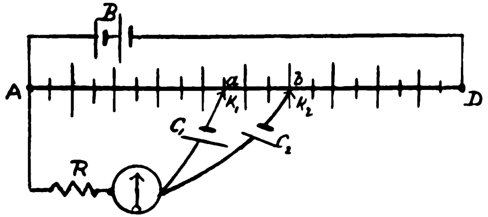

FIG. 41.

K_2, so as to be *in opposition to the battery* B. The other terminal of the galvanometer is connected through a resistance coil to A. Assuming that the potentiometer wire is of uniform section, the resistance between any two points, and consequently the D.P., will be proportional to the length of the wire between the two points, and the test consists in finding two points, a and b, in A D such that the D.P. between A and a, due to the battery B, balances the D.P. between the same points due to the cell C_1, in which case there will be no deflection of the galvanometer needle, and similarly with respect to the D.P. between A and b for the cell C_2. Let l_1 and l_2 denote the lengths Aa and Ab respectively, and e_1 and e_2 the E.M.F.s of the cells C_1 and C_2, and we shall have

$$\frac{e_1}{e_2} = \frac{l_1}{l_2} \text{ and } e_1 = \frac{l_1}{l_2} \times e_2 \quad . \quad . \quad . \quad . \quad (45)$$

It is a good plan to use a standard cell for C_2, of which the E.M.F., e_2, is known, and to keep the standard cell connected up whilst the cells to be tested take the place of C_1 in turn. For many purposes an ordinary Daniell's cell serves as a standard cell, and when in good condition its E.M.F. may be taken as 1·1 volt. The following example very clearly illustrates the principle underlying all potentiometer measurements :

Example.—A battery of 1 ohm resistance and E.M.F. E volts is connected to a uniform wire of 9 ohms resistance stretched over a scale 90 centimetres long. The D.P. between the ends of the wire is $\frac{9}{10}$E, and D.P.s of ·1 E, ·2 E, ·3 E, &c., will exist between points 10 centimetres, 20 centimetres, and 30 centimetres apart respectively along the wire. When the battery is replaced by another of the same resistance but of E.M.F. E_1 volts, it is found by means of a galvanometer that the D.P. between two points in the wire 20 centimetres apart is the same as the D.P. between two points 10 centimetres apart in the former case. Compare E and E_1.

In the first case $\frac{e_1}{E} = \cdot 1$ and $e_1 = \frac{1}{10}E$, In the second case $\frac{e_2}{E_1} = \cdot 2$ and $e_2 = \frac{2}{10}E_1$

$$\text{but} \quad e_1 = e_2 \therefore \frac{1}{10}E = \frac{2}{10}E_1$$

$$\therefore E = 2E_1, \text{ and } E : E_1 = 2 : 1.$$

Practical Exercise.—(1) Determine the E.M.F. of a Leclanché cell, Smee's cell, and Grove's cell by the potentiometer method (see fig. 41), using a Daniell's cell as the standard. It is important to notice that the E.M.F. of the battery must be greater than the E.M.F. of the cell under test. Tabulate the results as follows:

Experiment	l_1 for Cell C_1	l_2 for Cell C_2	Ratio $\frac{l_1}{l_2}$	E.M.F. of C_1	Description of cell

Experiment 8 E.—**Heating Effects of a Current.**

Apparatus.—Battery of three or four Daniell's cells, tangent galvanometer, reversing key, coils of high-resistance wire, water bath (fig. 42), and variable resistance.

Notes and Definitions.—Electrical energy produced by a voltaic cell may be transformed into an equivalent amount of *mechanical*, *chemical*, or *thermal* energy, and in all cases where the electrical energy is not expended usefully in one or other of these forms it is frittered away as *heat* in some part of the circuit. Advantage is taken of the fact that currents of electricity will produce heat in many commercial undertakings, such as electric lighting, electric heating, welding, and smelting. And it is evident that wherever resistance is concentrated, heat is manifested; consequently

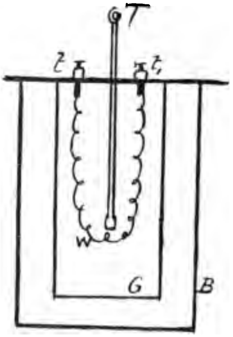

FIG. 42.

whenever a current of electricity passes along a wire, the temperature of that wire is raised to a greater or less extent. The quantity of heat developed in a conductor was found by Joule to be proportional

(1) to the square of the current;
(2) to the resistance of the conductor; and
(3) to the time.

The connection between these quantities and the heat developed is known as *Joule's Law*, which, stated algebraically, is as follows:

$$H = C^2 R t \times 0{\cdot}24 \qquad . \quad . \quad . \quad . \quad . \quad (46)$$

where C is the current in amperes, R the resistance in ohms, t the time in seconds, and H the number of units of heat.

Def.—The unit of heat is that amount of heat which will raise 1 *gramme of water through* 1° C. *of temperature, and is called the Calorie.*

Joule's Law may be easily verified. A section of the water-bath required is shown in fig. 42. G is a glass or brass vessel enclosed in a wooden box, B, large enough to allow a thick layer of sawdust to surround G. The conductor, W, of German silver, having a fairly high resistance, is attached to two terminals, t and t_1, fastened to a wooden lid, and is coiled into a loose spiral, as shown. When the cover is fitted on G, the conductor should be completely immersed, but should not touch the bottom or sides of the bath. A reliable thermometer, T, also passes through the cover, and it is important that the water should be repeatedly stirred by means of a glass rod passing through the cover before the readings of the thermometer are taken. The heat developed is found by taking the product of the weight of the water in grammes, and the number of degrees, C, of increase in the temperature. The resistance of the conductor should be determined beforehand.

Practical Exercises.—(1) Take about 18 inches of No. 40 copper and German silver wires, and send a current from three cells through each. Note which gets the hotter. Shorten the German silver wire gradually until 2 or 3 inches only are in circuit. Note what happens.

(2) Connect the water-bath in series with the battery and

tangent galvanometer, and allow the current to pass for five or ten minutes. Repeatedly stir the water, and note the temperature at the beginning and the end. Enter the results as follows :

Duration of test . . . . . . t seconds
Weight of water . . . . W grammes
Resistance of conductor . . . . . R ohms

Experiment	Temperature		$T_1 - T_0$	Galvanometer deflection α	$C = K \tan \alpha$	Heat developed	
	T_0 (beginning)	T_1 (end)				$C^2Rt \times 0{\cdot}24$	$W \times (T_1 - T_0)$

(3) Repeat the above with (1) different conductors, and (2) different currents.

(4) Determine the resistance of a conductor by the above method.

(5) Connect experimental tangent galvanometer (fig. 19), copper voltameter (fig. 22), and water-bath in series with a constant battery, and determine the connection between the *magnetic*, *chemical*, and *thermal* effects of a current.

Exercises.—(1) What sources of error have you noticed in the above experiments ?

(2) Prove that the current is proportional to

$$\sqrt{\frac{T_1 - T_0}{t}}.$$

(3) Plot a curve with the values of the rate of rise of temperature or increase of temperature every minute as abscissæ and tan α as ordinates. What do you learn from the shape of the curve ?

Experiment 8 F.—**Thermo-Electric Currents.**

Apparatus.—The same as in experiment 8 E, together with a German silver and iron couple, a thermometer, and water-bath, test tubes, alcohol, and ice.

Notes and Definitions.—If the junctions in a closed circuit formed of dissimilar metals are not all at the same temperature, an E.M.F. is set up, and a current, known as a *thermo-electric current*, traverses the circuit. Thus if a German silver wire, A, be soldered to an iron wire, B, as at C in fig. 43, and the free ends *a* and *b* of the German silver and iron wires respectively are connected to copper connecting wires so as to be joined to a galvanometer, as shown in the figure, the arrangement forms a thermo-electric couple. If the junction C be warmed so that its temperature is higher than the common temperature of *a* and *b*, a deflection of the galvanometer needle will be obtained, indicating that a current flows across the heated junction from the German silver to the iron—*i.e.* from B to A across C. If the temperature of C be lower than that of *a* and *b* the direction of the current is reversed. The electrical energy is due to the heat absorbed at the hot junction; and the *thermo-E.M.F.*, within certain limits, is proportional to the difference of temperature between the hot and cold junctions, and it continues so long as the difference of temperature is maintained. This phenomenon is known as the Seebeck effect.

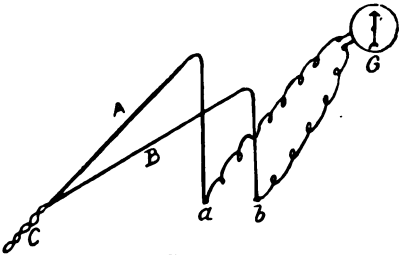

FIG. 43.

Practical Exercises.—(1) Enclose the ends *a* and *b* of the German-silver-iron couple in test tubes filled with alcohol. Note the galvanometer deflections when the junction C is at *the same*, *a lower*, and *a higher* temperature than *a* and *b*. The bare wires must not touch one another except at C.

(2) Determine the galvanometer deflection for every 5° C. increase of temperature up to 100° C. by placing the junction C in the water-bath.

(3) Determine by the potentiometer method the E.M.F. set up when C is at 100° C. and *a* and *b* at 0° C. (by means of ice) in terms of the E.M.F. of a Daniell's cell. Connect the couple in the place of the cell at E, of experiment 8 p.

CHAPTER IX

ELECTRO-MAGNETISM

Notes and Definitions.—The close connection existing between electricity and magnetism, to which we have already referred (Experiment 4 A), plays a most important part in the practical applications of electricity, and the following exercises have been arranged to explain the principles applied in the construction o electro-magnetic mechanism. The nature of the magnetic fields set up by a current are depicted in fig. 44, and the student is advised to trace the connection between the direction of the magnetic field due to a circular current (fig. 44 *d*) with the field due to a straight current (fig. 44 *a*). By means of fine iron filings sprinkled on cardboard, cut so as to pass inside a long coil of insulated wire, a map of the magnetic field accompanying the passage of electricity through the coil may be obtained, and it will be found that when the length of the coil is great compared with its diameter the field within the coil is fairly uniform, and that its direction is parallel to the axis of the coil, except at the ends.

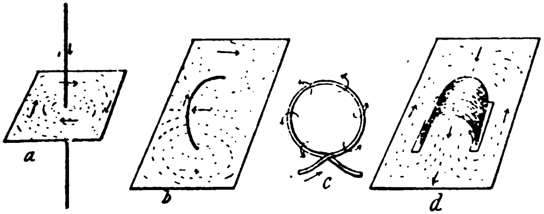

FIG. 44.

Externally the magnetic field exactly resembles that of an ordinary bar magnet, and, so far as its magnetic properties are concerned, the coil is an ironless magnet so long as the current lasts. It is important to notice that the magnetic field and properties completely disappear immediately the current ceases. Such a coil of wire is called an electro-magnetic spiral, helix or solenoid.

Def.—An electro-magnetic spiral, helix or solenoid is a coil of wire wound on a tube or bobbin, the diameter of which is small compared with its length.

By placing a small magnetic needle in the positions shown in fig. 44 *d*, it will be found that a solenoid through which a current is passing possesses polarity, and on reversing the direction of the current it will be found that the polarity is reversed. When the direction of the current is known, the polarity of a solenoid may be readily determined by the following rule :

Grasp the solenoid with the right hand so that the fingers point in the same direction as the current, then the thumb outstretched at right angles points in the direction of the N *pole of the solenoid.*

Conversely, if the polarity be known, the direction of the current may be determined. As would be expected from equation (21), Experiment 4 A, the intensity of the magnetic field is proportional to the current flowing and also to the number of turns of wire. The product of the current in amperes and the number of turns is known as *ampere-turns*, and the *magnetising force—i.e.* the force producing the magnetic field—*is therefore proportional to the number of ampere-turns.* And by experiment it may easily be proved that the magnetising force is constant so long as the ampere-turns are the same, whatever the separate values of the current and turns of wire may be. Thus 4 amperes flowing through 40 turns of wire produce the same magnetic field as 8 amperes flowing through 20 turns. If we denote the intensity of the field at the centre of the solenoid by H—*i.e. the number of lines of force per square centimetre*—it may be proved that

$$H = \frac{4 \pi C n}{l} = \frac{\cdot 4 \pi C' n}{l} \quad . \quad . \quad . \quad . \quad . \quad (47)$$

where C is the current in absolute units, C′ the current in amperes, and l the length of the solenoid in centimetres. And since $\cdot 4\pi = 1\cdot 257$, *the intensity of the field in a long solenoid is equal to* 1·257 *times the number of ampere-turns per centimetre of length of the solenoid.*

$4\pi C n$ or $\cdot 4\pi C' n$ is analogous to E.M.F. in the electric circuit, and is known as *magneto-motive force.*

Experiment 9 A.—**Comparison of Electro-magnetic Fields.**

Apparatus.—Magnetometer and scale (figs. 11 and 12 *a*). Tangent galvanometer, battery of constant cells, variable resistance, two exactly similar solenoids, compass needles, iron filings on cardboard, reversing key and connecting wires.

As the following tests are simple and similar to the magnetic tests already performed, it will only be necessary to point out one or two details. The dimensions of the bobbins for the solenoids are given in fig. 45, and each should be wound with eight layers of No. 20 or 22 well-insulated copper wire, divided up into four sections, each containing two layers having the same number of turns. By using five terminals as shown, one, two, three, or four sections may be used as desired.

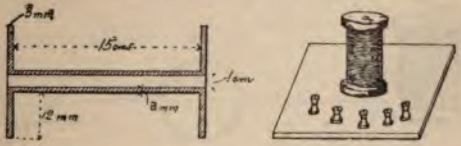

FIG. 45.

Practical Exercises.—(1) By means of iron filings sprinkled on cardboard obtain maps of the several magnetic fields shown in fig. 44, and by using a compass needle determine the direction of the magnetic field both for direct and reversed currents.

(2) Prove the rule for determining the polarity of a solenoid.

(3) Determine whether the current circulates clockwise or contra-clockwise when looking at the N pole of a solenoid. Do the same for the S pole.

(4) By the method of vibrations, Experiment 2 C, prove that H

is constant so long as the number of ampere-turns remains the same. The arrangement of the apparatus is shown in fig. 46.

Connect the tangent galvanometer, resistance, and battery in series with the solenoid, and when all the coils are in circuit, send about $\frac{1}{10}$ of an ampere through the circuit.

Determine the number of vibrations, n_1, both for the direct and reversed current. On taking one set of coils out of the circuit increase the current by one-third. Again, take the number of vibrations, n_2, and so on, keeping the ampere-turns the same, by varying the resistance in the circuit and noting the readings of the galvanometer.

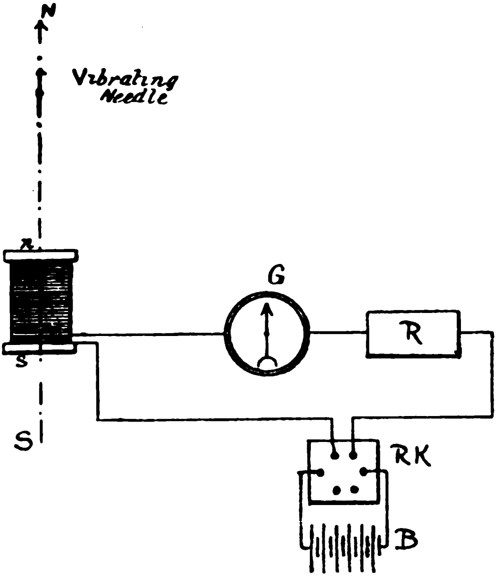

Fig. 46.

Note $\frac{n_1^2 - n^2}{n_2^2 - n^2} = 1$, n = vibrations due to earth's magnetism.

(5) Fix up the magnetometer and scale as in Experiment 3 B, the solenoid taking the place of the magnet in the 'end-on' position, and by means of the deflections compare the values of H when one, two, three, and four sets of coils are in circuit, the same current passing each time. The current may be maintained constant by inserting four sets of coils of the second solenoid in circuit with one set of the first solenoid. By taking one set of the second solenoid out of the circuit when an additional coil of the first is added, the resistance of the circuit remains constant. The arrangement of the apparatus is shown in fig. 47, S_1 being the solenoid under test, and S_2 the second solenoid; G the tangent galvanometer, which must be some distance from the magnetometer, M; R K is the reversing key. The distance between S_1 and M must be adjusted to give suitable deflection when the four sets of coils of S_1 are in use. Tabulate the results as follows :—

Experiment	Number of turns of S_1	Deflections			$\frac{\text{Mean deflection}}{\text{Number of turns}}$
		Direct	Reversed	Mean	

Exercises.—(1) On squared paper plot a curve, taking the ampere-turns as abscissæ and the deflections as ordinates. (2) Since there are 4π magnetic lines per unit pole, prove that the pole strength of a solenoid is

$$m = \frac{\pi r^2 C' n}{10 l} \text{ units.}$$

Note.—The total number of lines of force passing through the solenoid = H × area = $H \times \pi r^2$; r = radius of solenoid.

Magnetic Properties of Iron.—*Notes and Definitions.*—We are now in a position to consider the discovery made by Arago and Davy independently in 1820, *i.e.* that magnetic substances are magnetised by inserting them in a coil of wire through which a current is passing. When we remember that unmagnetised iron and steel become magnetised when placed in a magnetic field, it is easy to understand what takes place when a current

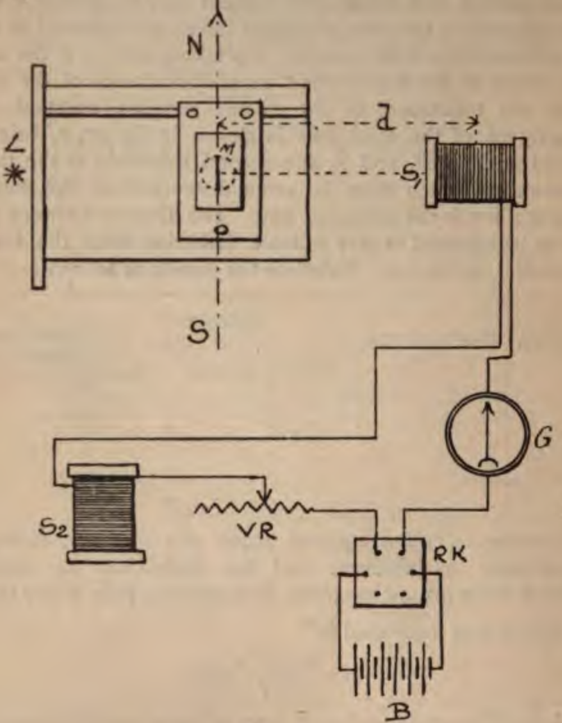

FIG. 47.

circulates round a piece of iron or steel. In fig. 48, H is a hollow coil, and B the same coil with a core of soft iron, the same current passing in each case. The upper figure is simply a magnetising coil, the magnetic field of which is of a definite intensity and easily determined by (47), and is represented by H lines per square centimetre. With the iron core inside, the intensity of the resulting field for the same current is represented by B lines, B being much greater than H, from which we see that the presence of iron increases the intensity of the field by (B – H) per square centimetre. What actually takes place is that the H lines due to the current magnetise the iron by induction, and thus *create* (B – H) lines in the iron core. The result of placing iron in the coil is twofold:

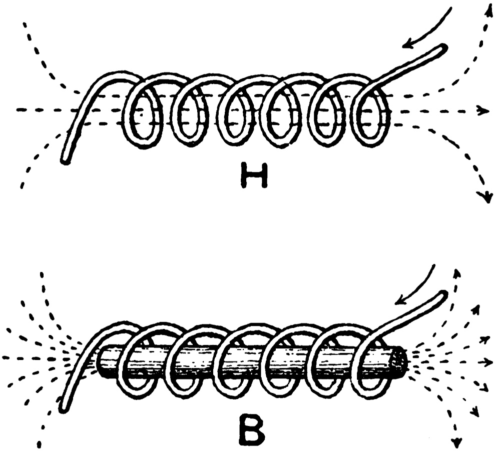

Fig. 48.

(1) It concentrates the lines of force, iron being a good conductor of magnetic lines, and

(2) Increases the number of lines by induction.

Iron is thus said to be more *permeable* to lines of magnetic induction than air, and the intensity of the magnetic field, or degree of magnetisation in the iron, which is denoted by B lines per square centimetre, is known as *magnetic induction.*

The ratio of B to H is symbolised by the Greek letter μ, and is known as the *permeability* of the iron. That is,

$$\frac{B}{H} = \mu, \text{ and } B = \mu \times H \qquad . \quad . \quad . \quad . \quad . \quad . \quad (48)$$

from which it is evident that μ, or permeability, is of the nature of a numerical coefficient, and denotes the *specific magnetic conductivity* of iron. The permeability of air is taken as the standard of reference, and is said to be unity. To take an example, if the induction in a sample of iron is denoted by 12,000 C.G.S. lines when the magnetic force is 15,

$$\text{the permeability} = \mu = \frac{B}{H} = \frac{12{,}000}{15} = 800;$$

that is, the permeability of this sample is 800 times that of the air under the same conditions. By experiment it is proved that permeability is a variable quantity, the value of μ changing with every change of H within certain limits. Permeability also varies with different samples of iron.

Experiment 9 B.—**Magnetisation of Iron.**

Apparatus.—Same as in 9 A, with the addition of several samples of iron wire, 16 centimetres long and No. 22 gauge, two rods of good soft charcoal iron, and two rods of hard steel 1 centimetre diameter and 16 centimetres long in both cases.

In these tests the samples of iron and steel are inserted in a solenoid, so that the centre of the core coincides with the centre of the coil; in the case of the iron wires it will be necessary to pass them through plugs of cork fixed in the solenoid, so that the wires coincide with the axis of the solenoid. As in Exercise 5 of Experiment 9 A, the solenoid is placed in the *end-on position* (fig. 4[illegible]), and the distance *d* must be adjusted, so that when the induction is a maximum the magnetometer deflection may be determined. Should the iron or steel exhibit magnetic properties previous to the test it must be thoroughly demagnetised. The magnetism induced is measured by noting the deflection of the magnetometer needle, and the intensity of magnetisation is expressed in terms of the earth's magnetism at the place where the test is being made. Previous to making the test for *induction* the value of H due to the current alone should be determined for each individual value of the current which it is intended to use. The strength of the current may be got from the readings of the tangent galvanometer, or by means of an ammeter taking its place.

Practical Exercises.—(1) With the apparatus connected up as in fig. 47, determine the magnetometer deflections when the number of turns on S_1 are varied, as in Exercise 5 of Experiment 9 A, the resistance of the circuit being maintained constant for each sample of iron and steel. Enter the results as follows :

Expt.	No. of turns of S_1	Magnetometer deflections α	$\frac{\text{Deflection}}{\text{No. of turns}}$	Moment of electro-magnet from $M = H\frac{d^3}{2} \tan \alpha$. H = Earth's magnetism	Strength of pole	Pole strength divided by $\frac{4\pi C n}{10 l}$

(2) Take each sample of iron wire, and determine the *induction* and the intensity of magnetisation by gradually increasing the magnetising force. Plot the results on squared paper, taking in each case the magnetising force as abscissa and the *induction* or *intensity of magnetisation* as ordinate. In each case also plot the curve for the hollow coil for corresponding magnetising forces, and by deducting the ordinates thus obtained from those of the induction curve, plot the curve giving $B - H$ On each sheet there will be three curves.

Method of making calculations :—

(1) Value of H (magnetising force) $= \frac{4\pi C n}{10 l}$.

(2) Value of magnetic moment from $M = \frac{H d^3}{2} \tan \alpha$ (see Experiment 3 B).

(3) Since magnetic moment, $M = m \times l$, $\therefore$ $m = \frac{M}{l}$.

(4) Number of lines of force issuing from pole.

There are 4π magnetic lines per unit pole, therefore the total number of lines of force due to solenoid and core

$$= 4\pi m.$$

(5) Value of $B = \frac{\text{total number of lines}}{\text{area}} = \frac{4\pi m}{A}$.

(6) Intensity of magnetisation of core $= I =$ pole strength of core per square centimetre of polar surface.

$$B - H = \text{magnetisation of core}$$
$$= 4\pi I.$$
$$\therefore \text{ I (intensity of magnetisation)} = \frac{B - H}{4\pi}.$$

(7) Permeability $= \frac{B}{H} = \mu$.

(8) Determine the deflection when the magnetising force is removed in the case of the soft iron and steel rods. What deductions may be drawn from the results thus obtained?

Experiment 9 C.—**Electro-magnets.**

Apparatus.—As in 9 B.

When soft iron is magnetised by a current circulating around it, the combination forms an *electro-magnet*, and it will have been observed from (3), above, that the core immediately loses its magnetism when the current ceases. On this account electro-magnets are of primary importance in many of the practical applications of electricity, and the following exercises are intended to demonstrate the essential features in the construction of electro-magnets. It is obvious from what has been said that the magnetism of an electro-magnet is proportional to the number of ampere-turns and to the permeability of the core. The connections for making the tests are shown in fig. 49, from which it will be seen that the two solenoids are placed side by side parallel to the meridian, and that the same current is sent through the two solenoids, so that a N. pole is adjacent to a S. pole. With this arrangement it is evident that the two poles form a magnet, the axis of which is at right angles to the meridian, the axis being the straight line joining the poles. Consequently the magnet is placed in the '*broadside position*' (Exp. 3 A), and its magnetic moment may be calculated from

$$M = H\, d^3 \tan a,$$

H being the earth's magnetism and a the deflection of the magnetometer. In fig. 49 the battery connections, which are the same as in fig. 47, are omitted. In fig. 50 the usual method of making electro-magnets is shown, together with the method for connecting the wire between the two limbs. When a yoke of soft iron is placed as at *a* in fig. 49, the electro-magnet is equivalent to the one shown in fig. 50. When the yoke is removed

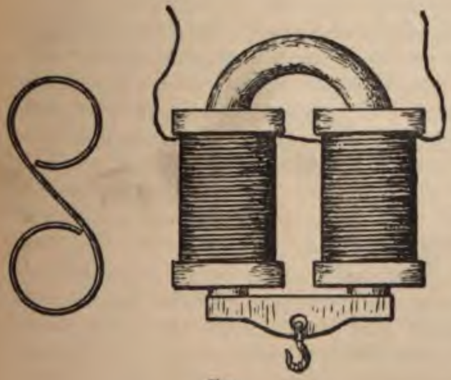

FIG.

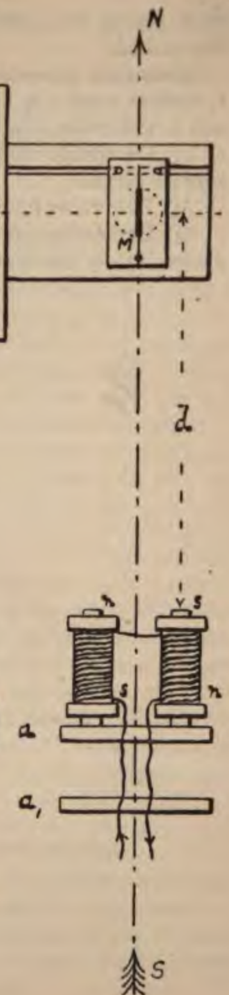

FIG. 49.

It is evident that relative motion may be produced in several ways, the following of which may be mentioned:

(1) By moving S or P;

(2) By stopping the current in P; this is equivalent to withdrawing S;

(3) By varying the strength of the current in P, and

(4) By making the current in P intermittent.

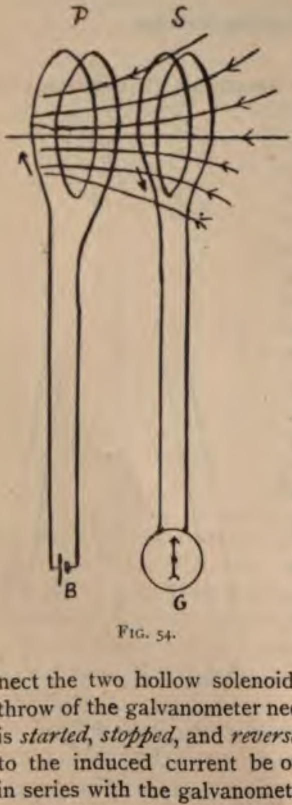

FIG. 54.

If the battery and galvanometer be interchanged we shall find that the result is the same, provided the conditions are the same, and the electrical pressure developed by varying the magnetic field embraced by S is termed the E.M.F. of *mutual induction*. The coil through which the current flows is known as the *primary coil* and is marked P, whilst the adjacent coil in which a current is induced is known as the *secondary coil*, and is marked S. As may be proved by experiment, the magnitude of the induced current is materially increased by inserting a soft-iron core in P, and is a maximum when the secondary coil surrounds the primary, their coils being co-axial, and their centres coincident.

Practical Exercises.—(1) Connect the two hollow solenoids as shown in fig. 55, and note the throw of the galvanometer needle when the current in the primary is *started*, *stopped*, and *reversed*. Should the extent of swing due to the induced current be off the scale, resistance may be added in series with the galvanometer.

(2) Determine the throw of the galvanometer needle when the

the first swing. From the results compare the intensity of the magnetic field at different points along *x y*. Do the same when the direction of motion is reversed.

Exercise (1).—From the results obtained above show on what the *magnitude* and *direction* of the E.M.F. depends.

Experiment 10 B. **Electro-induction.**

Apparatus, as in 10 A.

Notes and Definitions.—When we remember that currents of electricity set up magnetic fields we can readily understand that a current in a conductor also acts inductively upon neighbouring circuits. In fig. 54 P and S are two closed circuits placed near to one another, in the first of which a current is established. Consequently a magnetic field of constant intensity and permanent position relative to P is created, and *n* lines of this field thread through S, the value of *n* depending on the position of S relatively to P. The lines embraced by S will not vary so long as the current in P is constant, and consequently no E.M.F. exists in S, nor will any current be induced in S until the relative positions of S and the lines from P change. An induced E.M.F., however, is at once set up in S immediately relative motion takes place between the lines of force and the coils of S, in consequence of which the value of *n* changes, and a momentary induced current flows round S in the direction indicated, which is opposed to that of the inducing current.

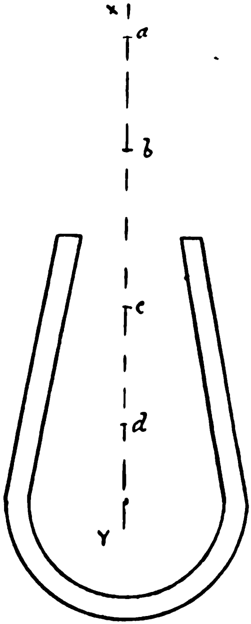

FIG. 53.

Experiment 10 C.—**Self-induction.**

Apparatus.—As above.

Notes and Definitions.—Since a current in a conductor acts inductively upon neighbouring conductors, it must also have a similar action upon itself whenever a change occurs in the strength of the current and an induced E.M.F. is developed in its own wires, the direction of the induced E.M.F. being opposite to the E.M.F. of supply. In other words, a back pressure is produced, the tendency of which is to obstruct the current in its own path. This back E.M.F. is greatest when a circuit is made or broken. Thus, on closing a circuit containing a battery and solenoid or electro-magnet, a definite fraction of time elapses before it establishes a current of constant strength, and during this time the E.M.F. of supply has to do work against the back pressure it is inducing. This phenomenon is known as *self-induction.*

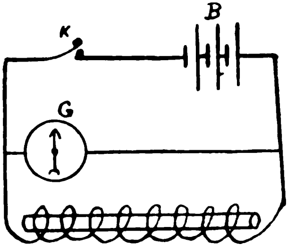

Fig. 56.

When such a current is broken, the magnetic field is gradually withdrawn from the coils, and this is equivalent to the magnetic field linking the coils from the opposite side, and the E.M.F. is thus in the same direction as the E.M.F. of the cell. Naturally the current itself tends to continue in motion, and in this it is assisted by the induced E.M.F., with the result that the pressure is so great that an exceedingly bright spark is produced. This property, in virtue of which a current 'tends to go on' when the circuit is broken, is sometimes termed 'electric inertia,' and this idea is very useful in assisting us to remember that it is impossible to produce any instantaneous change in a current when self-induction is present in a circuit.

Practical Exercises.—(1) Connect in series a battery of several cells, reversing key, and electro-magnet. Note the bright spark on breaking the circuit which appears at the point where the circuit is broken.

(2) Connect the mirror galvanometer as a shunt to an electromagnet, as shown in fig. 56. B is a powerful battery, and K is a make-and-break key. Block the needle so that it cannot be deflected by the battery current, whilst at the same time it is free to move in the opposite direction. Note the result when the circuit is made and broken.

Exercise.—(1) Explain the results obtained in (1) and (2).

APPENDIX

USEFUL TABLES.

E.M.F. of Cells.

Daniell's	1·07	volts	(approx.).
Grove's	1·9	,,	,,
Bunsen's	1·9	,,	,,
Leclanché	1·4	,,	,,
Bichromate	2·0	,,	,,

Specific Resistance of Metals at 0° *C. in Microhms.*

Copper	1·584	per	cm. cube, and	·6236	per	inch cube.
Silver	1·492	,,	,,	·5874	,,	,,
Platinum	8·982	,,	,,	3·536	,,	,,
Iron	9·637	,,	,,	3·794	,,	,,
Lead	19·47	,,	,,	7·665	,,	,,
Mercury	94·34	,,	,,	37·14	,,	,,
German silver	20·76	,,	,,	8·173	,,	,,
Platinoid	32·5	,,	,,	12·80	,,	,,
Manganin	47·5	,,	,,	18·7	,,	,,

Electro-chemical Equivalents.

Hydrogen	=0·000010384	grammes per	coulomb.
Silver	=0·0011181	,,	,,
Copper (Cupric)	=0·0003281	,,	,,
,, (Cuprous)	=0·0006562	,,	,,
Tin (Stannic)	=0·0003058	,,	,,
,, (Stannous)	=0·0006116	,,	,,
Iron (Ferric)	=0·0001935	,,	,,
,, (Ferrous)	=0·0002902	,,	,,
Nickel	=0·0003043	,,	,,
Zinc	=0·00033698	,,	,,
Lead	=0·0010716	,,	,,
Oxygen	=0·00008286	,,	,,

NATURAL SINES

—	0′	6′	12′	18′	24′	30′	36′	42′	48′	54′	1	2	3	4	5
°															
0	0000	0017	0035	0052	0070	0087	0105	0122	0140	0157	3	6	9	12	15
1	0175	0192	0209	0227	0244	0262	0279	0297	0314	0332	3	6	9	12	15
2	0349	0366	0384	0401	0419	0436	0454	0471	0488	0506	3	6	9	12	15
3	0523	0541	0558	0576	0593	0610	0628	0645	0663	0680	3	6	9	12	15
4	0698	0715	0732	0750	0767	0785	0802	0819	0837	0854	3	6	9	12	15
5	0872	0889	0906	0924	0941	0958	0976	0993	1011	1028	3	6	9	12	14
6	1045	1063	1080	1097	1115	1132	1149	1167	1184	1201	3	6	9	12	14
7	1219	1236	1253	1271	1288	1305	1323	1340	1357	1374	3	6	9	12	14
8	1392	1409	1426	1444	1461	1478	1495	1513	1530	1547	3	6	9	12	14
9	1564	1582	1599	1616	1633	1650	1668	1685	1702	1719	3	6	9	12	14
10	1736	1754	1771	1788	1805	1822	1840	1857	1874	1891	3	6	9	12	14
11	1908	1925	1942	1959	1977	1994	2011	2028	2045	2062	3	6	9	11	14
12	2079	2096	2113	2130	2147	2164	2181	2198	2215	2232	3	6	9	11	14
13	2250	2267	2284	2300	2317	2334	2351	2368	2385	2402	3	6	8	11	14
14	2419	2436	2453	2470	2487	2504	2521	2538	2554	2571	3	6	8	11	14
15	2588	2605	2622	2639	2656	2672	2689	2706	2723	2740	3	6	8	11	14
16	2756	2773	2790	2807	2823	2840	2857	2874	2890	2907	3	6	8	11	14
17	2924	2940	2957	2974	2990	3007	3024	3040	3057	3074	3	6	8	11	14
18	3090	3107	3123	3140	3156	3173	3190	3206	3223	3239	3	6	8	11	14
19	3256	3272	3289	3305	3322	3338	3355	3371	3387	3404	3	5	8	11	14
20	3420	3437	3453	3469	3486	3502	3518	3535	3551	3567	3	5	8	11	14
21	3584	3600	3616	3633	3649	3665	3681	3697	3714	3730	3	5	8	11	14
22	3746	3762	3778	3795	3811	3827	3843	3859	3875	3891	3	5	8	11	14
23	3907	3923	3939	3955	3971	3987	4003	4019	4035	4051	3	5	8	11	14
24	4067	4083	4099	4115	4131	4147	4163	4179	4195	4210	3	5	8	11	13
25	4226	4242	4258	4274	4289	4305	4321	4337	4352	4368	3	5	8	11	13
26	4384	4399	4415	4431	4446	4462	4478	4493	4509	4524	3	5	8	10	13
27	4540	4555	4571	4586	4602	4617	4633	4648	4664	4679	3	5	8	10	13
28	4695	4710	4726	4741	4756	4772	4787	4802	4818	4833	3	5	8	10	13
29	4848	4863	4879	4894	4909	4924	4939	4955	4970	4985	3	5	8	10	13
30	5000	5015	5030	5045	5060	5075	5090	5105	5120	5135	3	5	8	10	13
31	5150	5165	5180	5195	5210	5225	5240	5255	5270	5284	2	5	7	10	12
32	5299	5314	5329	5344	5358	5373	5388	5402	5417	5432	2	5	7	10	12
33	5446	5461	5476	5490	5505	5519	5534	5548	5563	5577	2	5	7	10	12
34	5592	5606	5621	5635	5650	5664	5678	5693	5707	5721	2	5	7	10	12
35	5736	5750	5764	5779	5793	5807	5821	5835	5850	5864	2	5	7	10	12
36	5878	5892	5906	5920	5934	5948	5962	5976	5990	6004	2	5	7	9	12
37	6018	6032	6046	6060	6074	6088	6101	6115	6129	6143	2	5	7	9	12
38	6157	6170	6184	6198	6211	6225	6239	6252	6266	6280	2	5	7	9	11
39	6293	6307	6320	6334	6347	6361	6374	6388	6401	6414	2	4	7	9	11
40	6428	6441	6455	6468	6481	6494	6508	6521	6534	6547	2	4	7	9	11
41	6561	6574	6587	6600	6613	6626	6639	6652	6665	6678	2	4	7	9	11
42	6691	6704	6717	6730	6743	6756	6769	6782	6794	6807	2	4	6	9	11
43	6820	6833	6845	6858	6871	6884	6896	6909	6921	6934	2	4	6	8	11
44	6947	6959	6972	6984	6997	7009	7022	7034	7046	7059	2	4	6	8	10
45	7071	7083	7096	7108	7120	7133	7145	7157	7169	7181	2	4	6	8	10
46	7193	7206	7218	7230	7242	7254	7266	7278	7290	7302	2	4	6	8	10
47	7314	7325	7337	7349	7361	7373	7385	7396	7408	7420	2	4	6	8	10
48	7431	7443	7455	7466	7478	7490	7501	7513	7524	7536	2	4	6	8	10
49	7547	7558	7570	7581	7593	7604	7615	7627	7638	7649	2	4	6	8	9
50	7660	7672	7683	7694	7705	7716	7727	7738	7749	7760	2	4	6	7	9
51	7771	7782	7793	7804	7815	7826	7837	7848	7859	7869	2	4	5	7	

NATURAL SINES—*continued*

—	0′	6′	12′	18′	24′	30′	36′	42′	48′	54′	1	2	3	4	5
°															
52	7880	7891	7902	7912	7923	7934	7944	7955	7965	7976	2	4	5	7	9
53	7986	7997	8007	8018	8028	8039	8049	8059	8070	8080	2	3	5	7	9
54	8090	8100	8111	8121	8131	8141	8151	8161	8171	8181	2	3	5	7	8
55	8192	8202	8211	8221	8231	8241	8251	8261	8271	8281	2	3	5	7	8
56	8290	8300	8310	8320	8329	8339	8348	8358	8368	8377	2	3	5	6	8
57	8387	8396	8406	8415	8425	8434	8443	8453	8462	8471	2	3	5	6	8
58	8480	8490	8499	8508	8517	8526	8536	8545	8554	8563	2	3	5	6	8
59	8572	8581	8590	8599	8607	8616	8625	8634	8643	8652	1	3	4	6	7
60	8660	8669	8678	8686	8695	8704	8712	8721	8729	8738	1	3	4	6	7
61	8746	8755	8763	8771	8780	8788	8796	8805	8813	8821	1	3	4	6	7
62	8829	8838	8846	8854	8862	8870	8878	8886	8894	8902	1	3	4	5	7
63	8910	8918	8926	8934	8942	8949	8957	8965	8973	8980	1	3	4	5	6
64	8988	8996	9003	9011	9018	9026	9033	9041	9048	9056	1	3	4	5	6
65	9063	9070	9078	9085	9092	9100	9107	9114	9121	9128	1	2	4	5	6
66	9135	9143	9150	9157	9164	9171	9178	9184	9191	9198	1	2	3	5	6
67	9205	9212	9219	9225	9232	9239	9245	9252	9259	9265	1	2	3	4	6
68	9272	9278	9285	9291	9298	9304	9311	9317	9323	9330	1	2	3	4	5
69	9336	9342	9348	9354	9361	9367	9373	9379	9385	9391	1	2	3	4	5
70	9397	9403	9409	9415	9421	9426	9432	9438	9444	9449	1	2	3	4	5
71	9455	9461	9466	9472	9478	9483	9489	9494	9500	9505	1	2	3	4	5
72	9511	9516	9521	9527	9532	9537	9542	9548	9553	9558	1	2	3	4	4
73	9563	9568	9573	9578	9583	9588	9593	9598	9603	9608	1	2	2	3	4
74	9613	9617	9622	9627	9632	9636	9641	9646	9650	9655	1	2	2	3	4
75	9659	9664	9668	9673	9677	9681	9686	9690	9694	9699	1	1	2	3	4
76	9703	9707	9711	9715	9720	9724	9728	9732	9736	9740	1	1	2	3	3
77	9744	9748	9751	9755	9759	9763	9767	9770	9774	9778	1	1	2	3	3
78	9781	9785	9789	9792	9796	9799	9803	9806	9810	9813	1	1	2	2	3
79	9816	9820	9823	9826	9829	9833	9836	9839	9842	9845	1	1	2	2	3
80	9848	9851	9854	9857	9860	9863	9866	9869	9871	9874	0	1	1	2	2
81	9877	9880	9882	9885	9888	9890	9893	9895	9898	9900	0	1	1	2	2
82	9903	9905	9907	9910	9912	9914	9917	9919	9921	9923	0	1	1	2	2
83	9925	9928	9930	9932	9934	9936	9938	9940	9942	9943	0	1	1	1	2
84	9945	9947	9949	9951	9952	9954	9956	9957	9959	9960	0	1	1	1	1
85	9962	9963	9965	9966	9968	9969	9971	9972	9973	9974	0	0	1	1	1
86	9976	9977	9978	9979	9980	9981	9982	9983	9984	9985	0	0	1	1	1
87	9986	9987	9988	9989	9990	9990	9991	9992	9993	9993	0	0	0	1	1
88	9994	9995	9995	9996	9996	9997	9997	9997	9998	9998	0	0	0	0	0
89	9998	9999	9999	9999	9999	1·0000 nearly	1·0000 nearly	1·0000 nearly	1·0000 nearly	1·0000 nearly	0	0	0	0	0

NATURAL SINES

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0	0000	0017	0035	0052	0070	0087	0105	0122	0140	0157	3	6	9	12	15
1	0175	0192	0209	0227	0244	0262	0279	0297	0314	0332	3	6	9	12	15
2	0349	0366	0384	0401	0419	0436	0454	0471	0488	0506	3	6	9	12	15
3	0523	0541	0558	0576	0593	0610	0628	0645	0663	0680	3	6	9	12	15
4	0698	0715	0732	0750	0767	0785	0802	0819	0837	0854	3	6	9	12	15
5	0872	0889	0906	0924	0941	0958	0976	0993	1011	1028	3	6	9	12	14
6	1045	1063	1080	1097	1115	1132	1149	1167	1184	1201	3	6	9	12	14
7	1219	1236	1253	1271	1288	1305	1323	1340	1357	1374	3	6	9	12	14
8	1392	1409	1426	1444	1461	1478	1495	1513	1530	1547	3	6	9	12	14
9	1564	1582	1599	1616	1633	1650	1668	1685	1702	1719	3	6	9	12	14
10	1736	1754	1771	1788	1805	1822	1840	1857	1874	1891	3	6	9	12	14
11	1908	1925	1942	1959	1977	1994	2011	2028	2045	2062	3	6	9	11	14
12	2079	2096	2113	2130	2147	2164	2181	2198	2215	2232	3	6	9	11	14
13	2250	2267	2284	2300	2317	2334	2351	2368	2385	2402	3	6	8	11	14
14	2419	2436	2453	2470	2487	2504	2521	2538	2554	2571	3	6	8	11	14
15	2588	2605	2622	2639	2656	2672	2689	2706	2723	2740	3	6	8	11	14
16	2756	2773	2790	2807	2823	2840	2857	2874	2890	2907	3	6	8	11	14
17	2924	2940	2957	2974	2990	3007	3024	3040	3057	3074	3	6	8	11	14
18	3090	3107	3123	3140	3156	3173	3190	3206	3223	3239	3	6	8	11	14
19	3256	3272	3289	3305	3322	3338	3355	3371	3387	3404	3	5	8	11	14
20	3420	3437	3453	3469	3486	3502	3518	3535	3551	3567	3	5	8	11	14
21	3584	3600	3616	3633	3649	3665	3681	3697	3714	3730	3	5	8	11	14
22	3746	3762	3778	3795	3811	3827	3843	3859	3875	3891	3	5	8	11	14
23	3907	3923	3939	3955	3971	3987	4003	4019	4035	4051	3	5	8	11	14
24	4067	4083	4099	4115	4131	4147	4163	4179	4195	4210	3	5	8	11	13
25	4226	4242	4258	4274	4289	4305	4321	4337	4352	4368	3	5	8	11	13
26	4384	4399	4415	4431	4446	4462	4478	4493	4509	4524	3	5	8	10	13
27	4540	4555	4571	4586	4602	4617	4633	4648	4664	4679	3	5	8	10	13
28	4695	4710	4726	4741	4756	4772	4787	4802	4818	4833	3	5	8	10	13
29	4848	4863	4879	4894	4909	4924	4939	4955	4970	4985	3	5	8	10	13
30	5000	5015	5030	5045	5060	5075	5090	5105	5120	5135	3	5	8	10	13
31	5150	5165	5180	5195	5210	5225	5240	5255	5270	5284	2	5	7	10	12
32	5299	5314	5329	5344	5358	5373	5388	5402	5417	5432	2	5	7	10	12
33	5446	5461	5476	5490	5505	5519	5534	5548	5563	5577	2	5	7	10	12
34	5592	5606	5621	5635	5650	5664	5678	5693	5707	5721	2	5	7	10	12
35	5736	5750	5764	5779	5793	5807	5821	5835	5850	5864	2	5	7	10	12
36	5878	5892	5906	5920	5934	5948	5962	5976	5990	6004	2	5	7	9	12
37	6018	6032	6046	6060	6074	6088	6101	6115	6129	6143	2	5	7	9	12
38	6157	6170	6184	6198	6211	6225	6239	6252	6266	6280	2	5	7	9	11
39	6293	6307	6320	6334	6347	6361	6374	6388	6401	6414	2	4	7	9	11
40	6428	6441	6455	6468	6481	6494	6508	6521	6534	6547	2	4	7	9	11
41	6561	6574	6587	6600	6613	6626	6639	6652	6665	6678	2	4	7	9	11
42	6691	6704	6717	6730	6743	6756	6769	6782	6794	6807	2	4	6	9	11
43	6820	6833	6845	6858	6871	6884	6896	6909	6921	6934	2	4	6	8	11
44	6947	6959	6972	6984	6997	7009	7022	7034	7046	7059	2	4	6	8	10
45	7071	7083	7096	7108	7120	7133	7145	7157	7169	7181	2	4	6	8	10
46	7193	7206	7218	7230	7242	7254	7266	7278	7290	7302	2	4	6	8	10
47	7314	7325	7337	7349	7361	7373	7385	7396	7408	7420	2	4	6	8	10
48	7431	7443	7455	7466	7478	7490	7501	7513	7524	7536	2	4	6	8	10
49	7547	7558	7570	7581	7593	7604	7615	7627	7638	7649	2	4	6	8	9
50	7660	7672	7683	7694	7705	7716	7727	7738	7749	7760	2	4	6	7	9
51	7771	7782	7793	7804	7815	7826	7837	7848	7859	7869	2	4	5	7	

NATURAL TANGENTS—*continued*

—	0′	6′	12′	18′	24′	30′	36′	42′	48′	54′	1	2	3	4	5
°															
52	1·2799	2846	2892	2938	2985	3032	3079	3127	3175	3222	8	16	23	31	39
53	1·3270	3319	3367	3416	3465	3514	3564	3613	3663	3713	8	16	25	33	41
54	1·3764	3814	3865	3916	3968	4019	4071	4124	4176	4229	9	17	26	34	43
55	1·4281	4335	4388	4442	4496	4550	4605	4659	4715	4770	9	18	27	36	45
56	1·4826	4882	4938	4994	5051	5108	5166	5224	5282	5340	10	19	29	38	48
57	1·5399	5458	5517	5577	5637	5697	5757	5818	5880	5941	10	20	30	40	50
58	1·6003	6066	6128	6191	6255	6319	6383	6447	6512	6577	11	21	32	43	53
59	1·6643	6709	6775	6842	6909	6977	7045	7113	7182	7251	11	23	34	45	56
60	1·7321	7391	7461	7532	7603	7675	7747	7820	7893	7966	12	24	36	48	60
61	1·8040	8115	8190	8265	8341	8418	8495	8572	8650	8728	13	26	38	51	64
62	1·8807	8887	8967	9047	9128	9210	9292	9375	9458	9542	14	27	41	55	68
63	1·9626	9711	9797	9883	9970	0̄057	0̄145	0̄233	0̄323	0̄413	15	29	44	58	73
64	2·0503	0594	0686	0778	0872	0965	1060	1155	1251	1348	16	31	47	63	78
65	2·1445	1543	1642	1742	1842	1943	2045	2148	2251	2355	17	34	51	68	85
66	2·2460	2566	2673	2781	2889	2998	3109	3220	3332	3445	18	37	55	74	92
67	2·3559	3673	3789	3906	4023	4142	4262	4383	4504	4627	20	40	60	79	99
68	2·4751	4876	5002	5129	5257	5386	5517	5649	5782	5916	22	43	65	87	108
69	2·6051	6187	6325	6464	6605	6746	6889	7034	7179	7326	24	47	71	95	118
70	2·7475	7625	7776	7929	8083	8239	8397	8556	8716	8878	26	52	78	104	130
71	2·9042	9208	9375	9544	9714	9887	0̄061	0̄237	0̄415	0̄595	29	58	87	115	144
72	3·0777	0961	1146	1334	1524	1716	1910	2106	2305	2506	32	64	96	129	161
73	3·2709	2914	3122	3332	3544	3759	3977	4197	4420	4646	36	72	108	144	180
74	3·4874	5105	5339	5576	5816	6059	6305	6554	6806	7062	41	82	122	162	203
75	3·7321	7583	7848	8118	8391	8667	8947	9232	9520	9812	46	94	139	186	232
76	4·0108	0408	0713	1022	1335	1653	1976	2303	2635	2972	53	107	160	214	267
77	4·3315	3662	4015	4374	4737	5107	5483	5864	6252	6646	62	124	186	248	310
78	4·7046	7453	7867	8288	8716	9152	9594	0̄045	0̄504	0̄970	73	146	219	292	365
79	5·1446	1929	2422	2924	3435	3955	4486	5026	5578	6140	87	175	262	350	437
80	5·6713	7297	7894	8502	9124	9758	0̄405	1̄066	1̄742	2̄432					
81	6·3138	3859	4596	5350	6122	6912	7920	8548	9395	0̄264					
82	7·1154	2066	3002	3962	4947	5958	6996	8062	9158	0̄285					
83	8·1443	2636	3863	5126	6427	7769	9152	0̄579	2̄052	3̄572					
84	9·5144	9·677	9·845	10·02	10·20	10·39	10·58	10·78	10·99	11·20					
85	11·43	11·66	11·91	12·16	12·43	12·71	13·00	13·30	13·62	13·95					
86	14·30	14·67	15·06	15·46	15·89	16·35	16·83	17·34	17·89	18·46					
87	19·08	19·74	20·45	21·20	22·02	22·90	23·86	24·90	26·03	27·27					
88	28·64	30·14	31·82	33·69	35·80	38·19	40·92	44·07	47·74	52·08					
89	57·29	63·66	71·62	81·85	95·49	114·6	143·2	191·0	286·5	573·0					

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